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RECOMMENDED METHODS OF REDUCTION, NEUTRALIZATION, RECOVERY, OR DISPOSAL OF HAZARDOUS WASTE

VOLUME III. DISPOSAL PROCESS DESCRIPTIONS. ULTIMATE DISPOSAL, INCINERATION, AND PYROLYSIS PROCESSES

TRW Systems Group

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The Solid Waste Research Laboratory of the National Environmental Research Center - Cincinnati, U.S. Environmental Protection Agency has reviewed this report and approved its publication. Approval does not signify that the contents necessarily reflect the views and policies of this Laboratory or of the U.S. Environmental Protection Agency, nor does mention of trade names of commercial products constitute endorsement or recommendation for use.

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in:

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

Under Section 212 of Public Law 91-512, the Resource Recovery Act of 1970, the U.S. Environmental Protection Agency is charged with preparing a comprehensive report and plan for the creation of a system of National Disposal Sites for the storage and disposal of hazardous wastes. The overall program is being directed jointly by the Solid and Hazardous Waste Research Laboratory, Office of Research and Development, National Environmental Research Center, Cincinnati, and the Office of Solid Waste Management Programs, Office of Hazardous Materials Control. Section 212 mandates, in part, that recommended methods of reduction, neutralization, recovery, or disposal of the materials be determined. This determination effort has been completed and prepared into this 16-volume study. The 16 volumes consist of profile reports summarizing the definition of adequate waste management and evaluation of waste management practices for over 500 hazardous materials. In addition to summarizing the definition and evaluation efforts, these reports also serve to designate a material as a candidate for a National Disposal Site, if the material meets criteria based on quantity, degree of hazard, and difficulty of disposal. Those materials which are hazardous but not designated as candidates for National Disposal Sites, are then designated as candidates for the industrial or municipal disposal sites.

A. W. Breidenbach, Ph.D., Director
National Environmental Research Center
Cincinnati, Ohio

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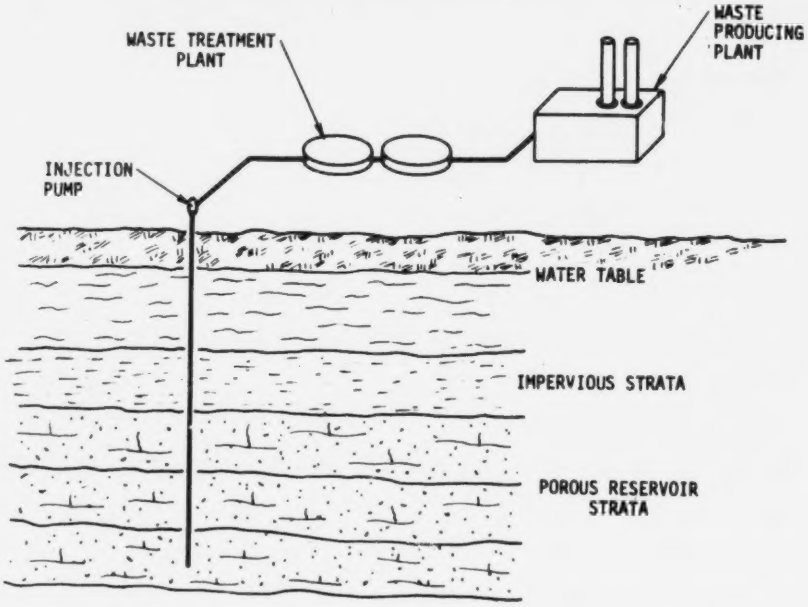
DEEP WELL DISPOSAL

1. INTRODUCTION

Deep well disposal is a system of disposing of raw or treated, filtered hazardous wastes by pumping the wastes into deep wells where they are contained in the pores of the permeable subsurface rock, separated from other groundwater supplies by impermeable layers of rock or clay. A generalized flow sheet is shown as Figure 1.



WASTE TREATMENT PLANT
WASTE PRODUCING PLANT
INJECTION PUMP
WATER TABLE
IMPERVIOUS STRATA
POROUS RESERVOIR STRATA

Figure 1. Deep Well Disposal

Because adequate surface disposal of wastes is usually quite expensive, the disposal of wastes in deep wells has been selected in many cases as being a practical and economical alternative for limiting pollution hazards.

Subsurface injection has been extensively and successfully used in the disposal of oil field brines ... there are now somewhere between 10,000 and 40,000 brine injection wells in the United States. The same principles can also be utilized in the design and installation of industrial waste disposal well systems.

Partly because of more stringent pollution legislation, the number of industrial waste injection wells completed in the United States has increased considerably over the recent past. From 1950 to 1963, 36 wells were completed; in the following 3 years, 39 more wells were installed; and by 1968, there were some 100 disposal wells in operation.

Injection wells can be used by virtually any type of industry which is located in the proper geologic environment and which has a waste product amenable to this method. A number of industries presently using the deep well injection method are shown below. The largest users of deep well disposal systems are the chemical and pharmaceutical industries.

	Percent
Chemical and pharmaceutical plants	50
Refineries	22
Steel and metal plants	7
Other, including paper mill, coke plants, etc.	21

The following discussion provides an overview of the various factors considered in the selection, design, construction, and operation of a deep well waste disposal facility. Much of the technical and procedural information presented below was obtained from an article[1523] by Mr. John Heckard of Dames and Moore, Consulting Engineers, from personal communications[1622] with Mr. Heckard, and from the report on deep well disposal by the National Industrial Pollution Control Council. The discussion of the various factors is followed by an assessment of the application of deep well disposal to hazardous wastes.

2. OPERATION PRINCIPLE

Deep well injection is actually a storage system, since the waste materials injected into the subsurface formations remain there indefinitely. The question of major importance is, therefore, "Under what conditions can deep subsurface strata be utilized for the storage of liquid wastes?"

To serve as an adequate liquid storage reservoir, an injection stratum must have sufficiently high porosity and permeability. Although under certain conditions all types of rocks are capable of storing injected fluids, porous sedimentary rocks (such as sandstone, limestone, and dolomite) are most likely to have the proper geologic characteristics required for waste injection.

An injection horizon must be separated from fresh water aquifers or any other usable natural resources by impervious confining strata such as clay or shale. The selection of a site, therefore, must provide for the protection of developed and undeveloped mineral resources, including ground water.

3. DESIGN

The design of an injection well is based on the depth of the well, the anticipated injection pressures, and the anticipated future maintenance requirements. In addition, state regulatory agencies often maintain specific requirements concerning the construction of waste injection wells; and, in all cases, the final design of the well must be approved by the appropriate state agency.

The construction details of a typical injection well are shown in Figure 2. In most cases, two or more well casings are used in the injection well. The customary procedure is to drill a large diameter hole through all fresh water aquifers. Casing is then inserted in the well, and the annular space is filled with cement.

If the formation to be used for injection is known in advance, drilling proceeds to the top of that formation, where a second string of smaller pipe is cemented in the hole from top to bottom. Then a smaller hole -- usually about eight inches in diameter -- is drilled through the injection formation. Injection tubing is placed in the casing and sealed at the top and bottom with packers. The well is then ready for testing.

If several rock zones need to be tested, the appropriate tests are performed in each zone as the hole is being drilled. Once the hole reaches the planned total depth, casing is installed and the annular space is grouted with cement. The well is then completed by perforating the casing and the cement at the appropriate zones.

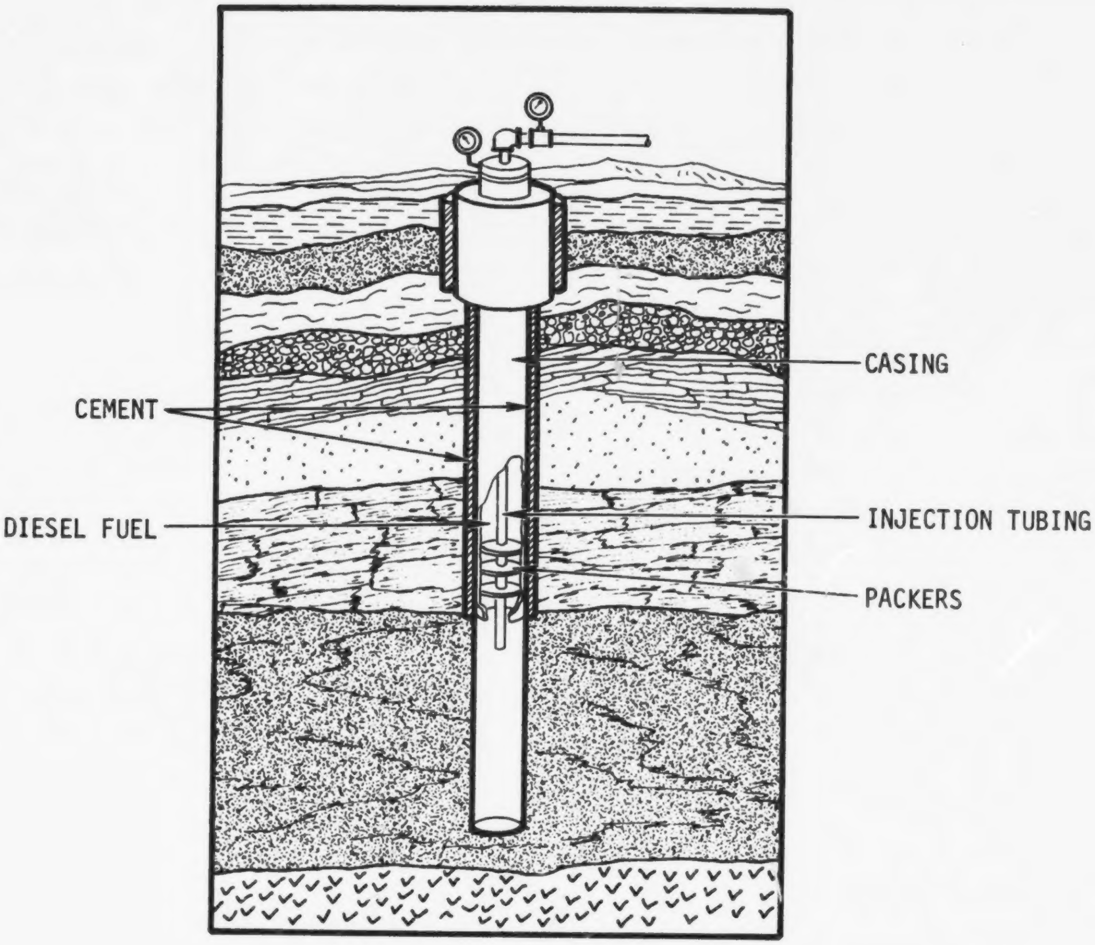

CASING
CEMENT
DIESEL FUEL
INJECTION TUBING
PACKERS

Figure 2. Typical Injection Well

The annular space between the injection tubing and the casing may be filled with an inert fluid such as diesel fuel. A pressure recording gauge is installed to measure changes in pressure in the annular space. Should either the tubing or the casing develop a leak, a pressure change would be recorded. In some instances, the fluid in the annular space is maintained under a pressure higher than that in the injection tubing. Then, if a break in the tubing occurs, the effluent will not leak into the annular space.

Wells presently in use range from about 300 feet to more than 12,000 feet in depth; the depths of a sample of 75 wells now in use are as follows:

Depths of Well	Percent of Total Wells
0-1000 feet	7
1000-2000 feet	29
2000-4000 feet	22
4000-6000 feet	31
6000-12,000 feet	9
greater than 12,000 feet	2

Effluent Treatment

Often it is necessary to treat the liquid waste to avoid detrimental reactions during the injection process. The required treatment depends on the amount and size of the solids suspended in the waste, the pore sizes of the formation to be injected, the chemical compatibility of the effluent and the formation fluids, and the corrosiveness of the effluent. The removal of suspended solids may not be necessary if the injection zones are composed of limestone or dolomite, since these rocks have rather large pores.

Surface storage facilities are usually included in the design of deep well disposal systems. Commonly, cement-lined sumps or steel tanks are used. An oil layer is frequently used to prevent contact of the effluent with the air. However, if there is oil in the effluent, it is generally removed before injection because it tends to plug the injection zone. Oil may be removed by first passing the waste through a settling tank equipped with internal baffles and then through a clarifier or a sedimentation tank designed to remove the suspended solids. The sedimentation process can be accelerated by using a flocculation or coagulation agent such as aluminum sulphate or ferric sulphate.

Coagulation and sedimentation may not adequately prepare the effluent for injection. Where sand and sandstone injection zones are susceptible to plugging, filtration is included as a part of waste treatment. The filters may consist of a series of metal screens coated with diatomaceous earth. If the waste contains microorganisms, some chemical treatment may also be required. Generally, five types of microorganisms can interfere with the subsurface injection system: slime formers, algae, iron bacteria, sulphate-reducing bacteria, and fungi.

Often the cost of the effluent treatment facilities exceeds the cost of drilling, testing, and constructing the injection well; but nevertheless this treatment is less expensive than the treatment which would be required to render the effluent acceptable for discharge into streams.

Operation of Injection Wells

Three critical factors which control the operation of an injection well are: (1) the compatibility of the effluent with the formation and the formation fluids; (2) the injection pressure; and (3) the injection rate.

Effluent Compatibility. The physical and chemical properties of the effluent are extremely important. The pores of the injection horizon can be plugged by suspended solids or dissolved gas contained in the effluent. Plugging can also be caused by chemical reactions between the effluent and the aquifer materials, or between the effluent and the native water in the injection zone. Plugging of the pores results in a decrease in porosity of the storage formations which, in turn, causes a reduction in well capacity.

Precautions to minimize the possibility of chemical reactions between the effluent and the aquifer materials were discussed in the preceding section. The various chemical reactions between injected and native water have been studied in some detail by various researchers. Although the exact influence of such reactions on aquifer permeability is uncertain, they will often cause undesirable results.

Sometimes when chemical reactions between injected and intersticial fluids are anticipated, the injection of a neutral fluid such as treated water has been successful in forming a buffer zone between the injected wastes and the interstitial fluids. Mathematical calculations substantiated by laboratory experiments have shown that longitudinal effluent dispersion will increase with the square root of the time or distance of flow. The size of the neutral buffer zone necessary to prevent reaction can be related to the undiluted width of the buffer zone by taking into account the total pore space in the buffer zone. Generally, preventing a chemical reaction from occurring within 100 feet of the well bore is sufficient. For more critical conditions it may be necessary to consider the dispersion coefficient and the viscosities of the fluids. It is important, however, that the two injected fluids do not bypass each other in the formation.

Injection Pressure. The injection pressure of a well consists of the sum of the injection zone pressure and the friction head losses due to the flow of the fluid through the well and into the injection zone. Proper injection well design can minimize such head losses. For example, they can be held at a minimum if the formation porosity is not reduced by sedimentation or flocculation within the injection formation. Also, artificial stimulation of the aquifer can sometimes increase the porosity of the formation in the vicinity of the well.

Generally, injection pressures vary with the depth of the well, but most injection pressures are less than 200 psi. The range of injection pressures for wells presently in use is shown below. High injection pressures are usually undesirable not only because they restrict the rate of effluent injection but also because they require considerably more expensive equipment. The well itself must then be designed to withstand higher pressures.

Injection Pressure, psi	Percent of Total Wells
partial vacuum	14
0-150	29
150-300	27
300-600	9
600-1500	20
greater than 1500	1

Injection Rate. Most of the problems that arise during the operation of an injection well are related to the rate of injection. Usually, an optimum injection rate can be established for each well; to exceed this rate might result in operational problems. Data regarding the injection rates of wells presently in use is as follows:

Injection Rate, GPM	Percent of Total Wells
0-50	27
50-100	17
100-200	25
200-400	26
400-800	4
greater than 800	1

Sometimes it is necessary to increase the porosity and permeability of the injection formation to produce an increase in the injection rate. This can be achieved by acidizing or fracturing the injection zone. Acidizing increases the effective permeability of limestone and dolomite formations in the vicinity of the well bore by dissolving certain minerals such as calcium carbonate. Fracturing increases the permeability by breaking up the rock or by enlarging pre-existing fractures by hydraulic or detonation methods. It is important, however, that fractures created by this process do not extend vertically through confining layers, since ground water contamination might then occur.

4. PROCESS ECONOMICS

In 1963, the cost of complete deep well disposal installations ranged from $30,000 to $1,400,000. In the least expensive system, no surface equipment was required for treating the waste; and the well was only 1,800 feet deep. The most expensive system included a treatment plant with a clarifier, dual filters, and four positive displacement pumps for injection into a 12,000-foot-deep well.

Currently, the cost of deep well disposal ranges from 50 cents to $2.00 per thousand gallons injected. This cost depends upon many variables including the depth of the well, the type of well completion, injection pressure, and treatment equipment required.

Cost analysis for a typical well -- about 3,000 feet deep -- indicates that drilling, completing, and testing would cost less than $150,000. The cost of necessary treatment facilities would be additional expenses and dependent on the particular requirements of the wastes and the site.

5. OTHER FACTORS TO BE CONSIDERED

Legal Requirements

Before starting a deep well disposal project, it is essential to discuss the plan with the appropriate regulatory agency and to obtain the necessary approvals. In about 34 states the construction of waste injection wells is subject to certain requirements. Only 3 states, Missouri, Ohio and Texas, have laws specifically governing wells for the disposal of industrial wastes. Most other states do not rule out the use of injection wells, but they often lack favorable geologic conditions and, therefore, do not have suitable sites for injection wells. Some states do not allow the use of deep well injection. If the geology is suitable and if the plans for well construction are adequate, authorization to proceed is generally given; but if a reasonable doubt exists in the minds of regulatory officials, subsequent hearing may be required.

In some cases, conditional permits are issued. For example, a permit may limit the maximum injection pressure which may be used, or it may stipulate that one or more formation pressure monitoring wells must be included in the project.

Regional Considerations

The specific location of a waste injection well must be evaluated by a detailed geologic subsurface investigation. However, regional geologic conditions can be used to evaluate whether certain areas are generally suitable for injection wells.

The regional favorability map (Figure 3) indicates that certain areas of the continental United States such as the Rocky Mountains are generally unsuitable for waste injection wells because igenous or metamorphic rocks lie near the ground surface (gray areas in the figure). Such rocks do not have sufficiently high porosity to warrant their use as a disposal formation. Areas underlain by extensive layers of volcanic rock (triangles on map) generally are not suitable for waste disposal wells. Even though these rocks have porous zones, they generally contain fresh water. The waste disposal potential of the Basin and Range Provinces (see angled lines on map) is largely unknown owing to complex geologic conditions.

While the central valley of California is geologically well suited for the installation of disposal wells, several factors discourage their use. Thick sequences of sandstone in the region provide suitable injection horizons; but discontinuities in pervious strata, earthquake hazards, and presence of extensive oil and gas accumulations are negative factors. Although the geology of the West Coast is complex, coastal areas north of Los Angeles may contain satisfactory potential sites for injection wells.

The Atlantic and Gulf coastal plains are underlain by thick sequences of sedimentary rock which, except in oil and gas producing areas, are generally suitable for deep well injection. The midcontinent and much of the Midwest are underlain by rather thick sequences of sedimentary rocks. Most of the injection wells in use today are located in these areas.

Geologic Investigations and Field Tests

The final appraisal of a disposal well site is usually determined by a two-phased geologic investigation. The first phase includes an evaluation of potential sites on the basis of available data. The second phase consists of a more detailed evaluation of subsurface conditions based on information obtained from drilling a pilot hole or the injection well.

Information sought during the first phase of the investigation and prior to the installation of an injection well includes the extent, thickness, depth, porosity, permeability, temperature, water quality, and hydrostatic pressure of potential injection zones. The presence of impermeable confining beds, lateral changes in rock properties, the existence of faults or joints, and the occurrence of any mineral resource in the area must also be evaluated. Existing wells in the area which may penetrate the potential injection zones must be located since, if not properly plugged, liquid wastes could escape through these wells.

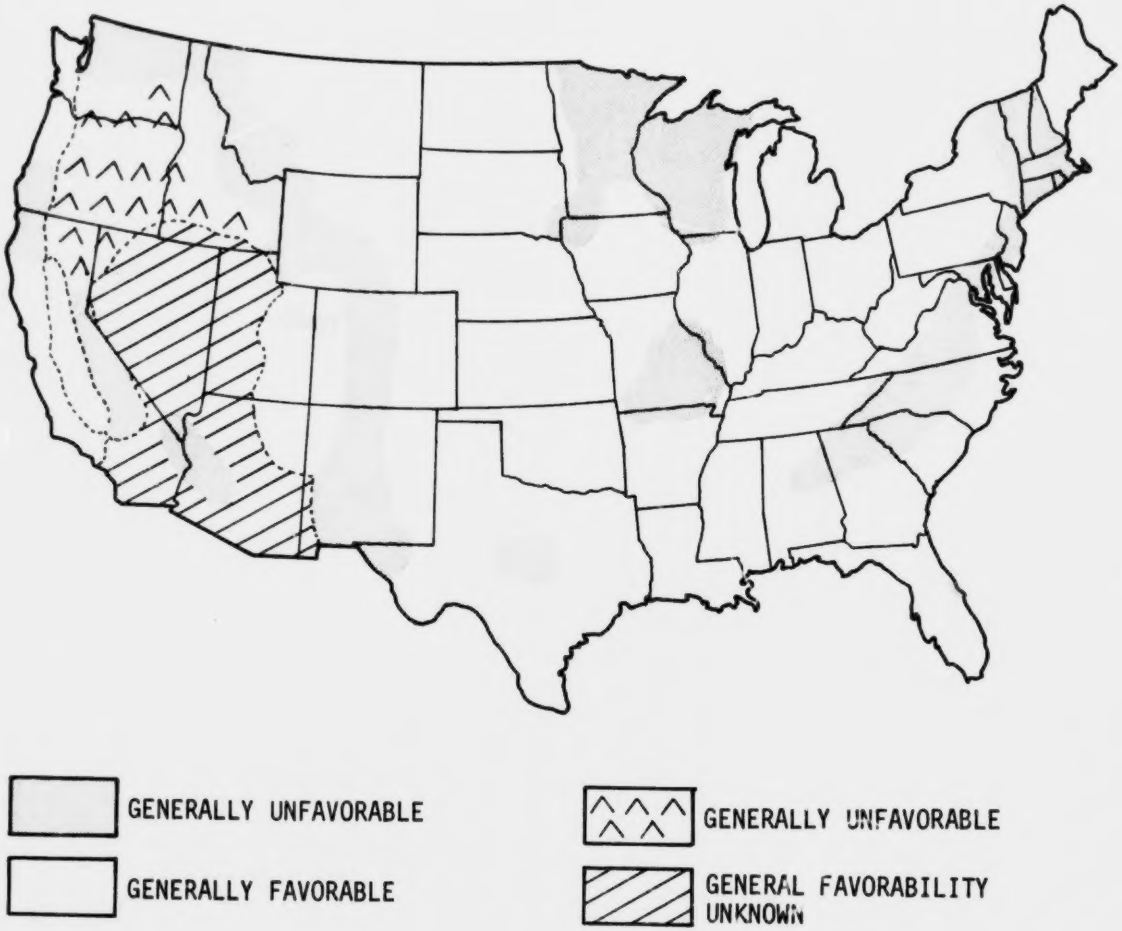

GENERALLY UNFAVORABLE
GENERALLY FAVORABLE
GENERALLY UNFAVORABLE
GENERAL FAVORABILITY UNKNOWN

Figure 3. Deep Well Disposal Sites

The second phase of the investigation is conducted during the drilling and testing of the injection well. Often the actual injection zone is not selected until the well has been drilled and a number of potential zones have been tested for porosity, permeability, temperature, and hydrostatic pressure, and the chemical quality of water in the potential injection zones has been evaluated. Pumping tests are used to measure the permeability, and water samples are obtained for chemical analysis. Other important rock properties are measured by geophysical logging, drill-stem testing tolls, or by laboratory tests on the core samples. The results of these geologic investigations are used not only in evaluating the feasibility of subsurface waste disposal but also to provide basic data for designing the injection well and the optimum rate of injection.

Wastes may have different requirements relating to their extent of horizontal and vertical travel with time. For example, a chemically stable dilute waste may require only injection into, and dispersion in, a body of rapidly circulating ground water that is recharged continually. However, biochemically unstable effluent may require a residence time within the injection zone to permit further reaction. As an example, a very concentrated waste may require a long residence time without dispersion. A system of zone classification has been proposed as follows:

Zone of Rapid Circulation. The zone of rapid circulation extends from the land surface downward some tens or hundreds of feet. Injection into this zone is normally precluded.

Zone of Delayed Circulation. This zone is generally composed of fresh water which circulates continually and freely, but is retarded sufficiently so that the residence time if of the order of several decades or even centuries. Certain innocuous waste waters have been injected into this zone successfully with suitable monitoring.

Subzone of Lethargic Flow. In this subzone the native liquid is commonly saline and has very low movement measured in hundreds or even thousands of years. This subzone of lethargic flow is a primary zone for potential storage of the more concentrated wastes.

Stagnant Subzones. These subzones are, with few exceptions, several thousand feet below land surface, and the fluid is hydrodynamically trapped. This zone would seem ideal for injection of very toxic waste. However, the capability to accept and retain injected fluids needs to be assessed with extreme caution.

Dry Subzones. A common type of dry subzone would be a salt bed or dome in which free water is virtually nonexistent, and which may be impermeable in a finite sense. Waste injected in such a zone would be wholly isolated from natural hydrodynamic circulation. However, since movement could occur through hydrofractures, performance of a dry subzone under injection should be assessed cautiously.

It is recommended that research be done to coordinate the limits of the various zones mentioned and to associate such zones with the various categories of wastes. In this manner, further information can be gathered.

6. RECOMMENDATION ON THE APPLICATION OF DEEP WELL DISPOSAL

In the past, there has not been enough attention given to the monitoring of deep well disposal systems. It is desirable to monitor injection wells to determine the extent of travel of injected waste permitting the detection of well casing or cement failures, the escape of waste through fractured or faulted cap rocks, or through other abandoned or operating wells, and the loss of permeability in the injection horizon during injection.

Monitoring is also required to determine the pressure needed to maintain a constant injection rate, since this increases with time. An increase in pressure probably indicates decreased permeability. A sudden increase in the intake rate of the injection well might indicate the opening of horizontal or vertical fractures in the injection horizon and possibly in the confining beds, or the failure of such well facilities as the casing, cement, or packers.

Such monitoring activities need to be documented and be made requirements of State and Federal laws relating to deep well disposal.

Related to monitoring requirements is the necessity for developing adequate planned methods and procedures to be followed to rapidly institute corrective actions in the event of a system failure. It is recommended that research be done to establish a list of the proper monitoring methods and implementation methods associated with deep well disposal and to develop procedures for instituting corrective actions in the event of a system failure.

In addition, complete operating records are required to denote quantities and types of waste injected into a particular stratum. Requirements for such records need to be part of State and Federal legislation.

The use of deep well disposal techniques should be limited at the present state-of-the-art to those waste stream constituents which have low toxicity in themselves and which also do not have breakdown or expected reaction products demonstrating high toxicity. This recommendation is based primarily on the apparent lack of control over wastes following injection. Without proper and adequate monitoring techniques the migration of hazardous materials from the "storage" area may not be detected until there is an effect on the non-storage area (ground water contamination, etc.) when it might be too late. Furthermore, given that an unexpected migration is detected there are currently no tested procedures which will reverse the migration or allow total recovery of the materials, or seal the periphera to insure halting the migration.

In summary, deep well disposal methods can be utilized subject to detailed geological investigations and selection, rational selection of wastes to be so disposed and proper monitoring of the sites so that disposal can be stopped at the proper time without fear of migration.

7. REFERENCES

0844. National Industrial Pollution Control Council. Waste disposal in deep wells. Government Publication 55-95. Feb. 1971. 34 p.

1573. Heckard, John. Deep well injection of liquid wastes. Engineering Bulletin No. 35. Los Angeles, Dames & Moore, 1970. 6 p.

1622. Personal communication. G. Melickian, Dames & Moore, to A. Lee, TRW Systems, Apr. 19, 1972.

LAND BURIAL DISPOSAL

1. INTRODUCTION

Land burial is adaptable to those hazardous materials that require permanent disposal. Disposal is accomplished by either near-surface or deep burial. In near-surface burial the material is deposited either directly into the ground or is deposited in stainless steel tanks or concrete lined pits beneath the ground. The standard procedures for deep burial are disposal in salt mines or hard bedrock, or in shale formations by using hydraulic fracturing. Hydraulic fracturing is not covered here but is covered under deep well disposal.

In land burial the waste is transported to the selected site, where it is prepared for final burial. Transportation of the wastes to the burial site can be accomplished in three ways: by common carriers with the waste packaged along with ordinary shipments of wastes, by contract carriers that handle only the hazardous materials to be buried but collect from various sources, or by private carriers that transport their own wastes from the point of origin to the burial site.

Either solid or liquid wastes can be received at the burial site. To reduce the mobility of the wastes before burial all liquid wastes should be converted to a solid form. This requires that special solidification equipment be located at the burial site. Coupled with this special solidification equipment heavy equipment for excavation and lifting and special monitoring instruments and stations will also be required.

At the present time near-surface burial of both radioactive and chemical wastes are being conducted at several Atomic Energy Commission (AEC) and commercially operated burial sites.[1423] These wastes are buried in unlined trenches approximately 20 ft in depth. The trenches are filled to within 2 to 5 ft of the surface and are covered with either asphalt or soil and vegetation to reduce infiltration of water. Radioactive wastes are stored in either liquid or solid form in steel tanks enclosed in concrete.[0705,0710]

Pilot plant studies have been conducted for deep burial in salt formations [0696, 0957] and hard bedrock.[0738] These wastes would be buried approximately 1,000 to 1,500 ft beneath the ground in unlined tunnels. The wastes are lowered into these tunnels by means of a central access shaft. After the filling operation is complete in a tunnel, it is sealed off by backfilling with salt and using a positive seal (e.g.,concrete).

2. OPERATION PRINCIPLES

Land burial operates on the principle of permanent confinement and isolation from the biosphere. The wastes can be disposed of near the surface in specially constructed trenches or pits that are designed to retain the wastes and prevent infiltration into the soil. They can also be buried deep beneath the ground where better isolation from the biosphere is afforded. For either method the form of the waste, type of container, and site geology are of utmost importance in determining the suitability of any land burial disposal process.

3. DESIGN

This section describes the factors related to site selection and type of monitoring system required. In addition, the design of current land burial disposal operations is discussed.

Site Selection

The selection of a site for the disposal of hazardous materials is dependent upon several factors. These include physical characteristics of the wastes to be buried, environmental characteristics of the area, operating equipment and waste handling procedures required, and the geographic characteristics of the surrounding area.

The types of hazardous wastes to be buried at a particular disposal site are important in determining whether the site is owned and operated by a private concern or by the government. If only short-lived materials are to be disposed of then private ownership and operation with state or federal licensing and regulation can be considered. For long-lived materials it is imperative that the disposal site be located on state or federally owned land to ensure that perpetual monitoring and care can be maintained. Even though government ownership of the site is required, on-site operation can be performed by a private concern.

In selecting the location of a disposal site the environmental characteristics of the area are important. The environmental factors of principal concern are meteorology, geology, hydrology, and geoseismology. Detailed meteorological data are required since if a particle or gas escapes to the outside environment, its fate is determined by the prevailing meteorological conditions. The frequency of wind direction toward any given sector determines the degree of possible risk to the population within that sector from material emitted upwind. Besides wind direction, wind speed affects the dilution rate of the material. The amount and rate of rainfall are significant factors in determining the amount of material that can be leached from the wastes.

The geology and hydrology of the area determine whether waste is dispersed or confined. The factors which influence the movement of the waste are: main formations in the area, such as gravel, clay, sand, and shale; permeability and ion exchange capacity of the soil; and depth of the water table.

Since water represents the main vehicle of transporting any significant quantities of wastes from the burial site, the site should be as far as possible from any important ground water sources. Since the ground water can convey the wastes to the surface streams, it is necessary to determine the possible movement of ground water from the burial site into the streams, springs, and water sources. The points of ground water discharge must be established and the dilution capacity of the surface streams determined.

In near-surface burial the trenches or concrete and stainless steel lined pits should be constructed to hold the wastes above the water table. This is to prevent leaching of the waste by the ground water. The wastes should also be buried as far as possible from any surface stream or water wells in order to maximize the retention time in the soil if leaching of the wastes does occur. In this way the waste can be retained by the natural processes of absorption, filtration, and ion exchange. The trenches or pits should be covered with an impermeable material to prevent infiltration of rainfall. Infiltration of rain can be prevented by covering with cement or by covering with clay or shale and capping with asphalt. Also, infiltration of rain can be reduced by covering with grass or other vegetation. This latter method is less desirable than the other two since some infiltration of water can occur especially during periods of heavy rainfall.

The geoseismology data such as faults, vibrations, and tsunamis are the major earthquake phenomena that must be considered. Since there is a general lack of knowledge about earthquakes, it is necessary to make conservative estimates and evaluations of the critical geoseismological data. A seismic probability map of the United States is shown in Figure 1 depicting zones of no, moderate, and major damage. The largest zone of possible major seismic damage lies along the west coast of the United States.

In locating the disposal site it is necessary to provide sufficient distance between the site and the surrounding population to minimize the danger to the general public by either normal operation or accidental releases. For nuclear reactor plants federal regulations (10CFR100) specify that the reactor plant be surrounded by a zone of low population. This same regulation should also apply to a disposal site of hazardous materials. A population density map of the United States is shown in

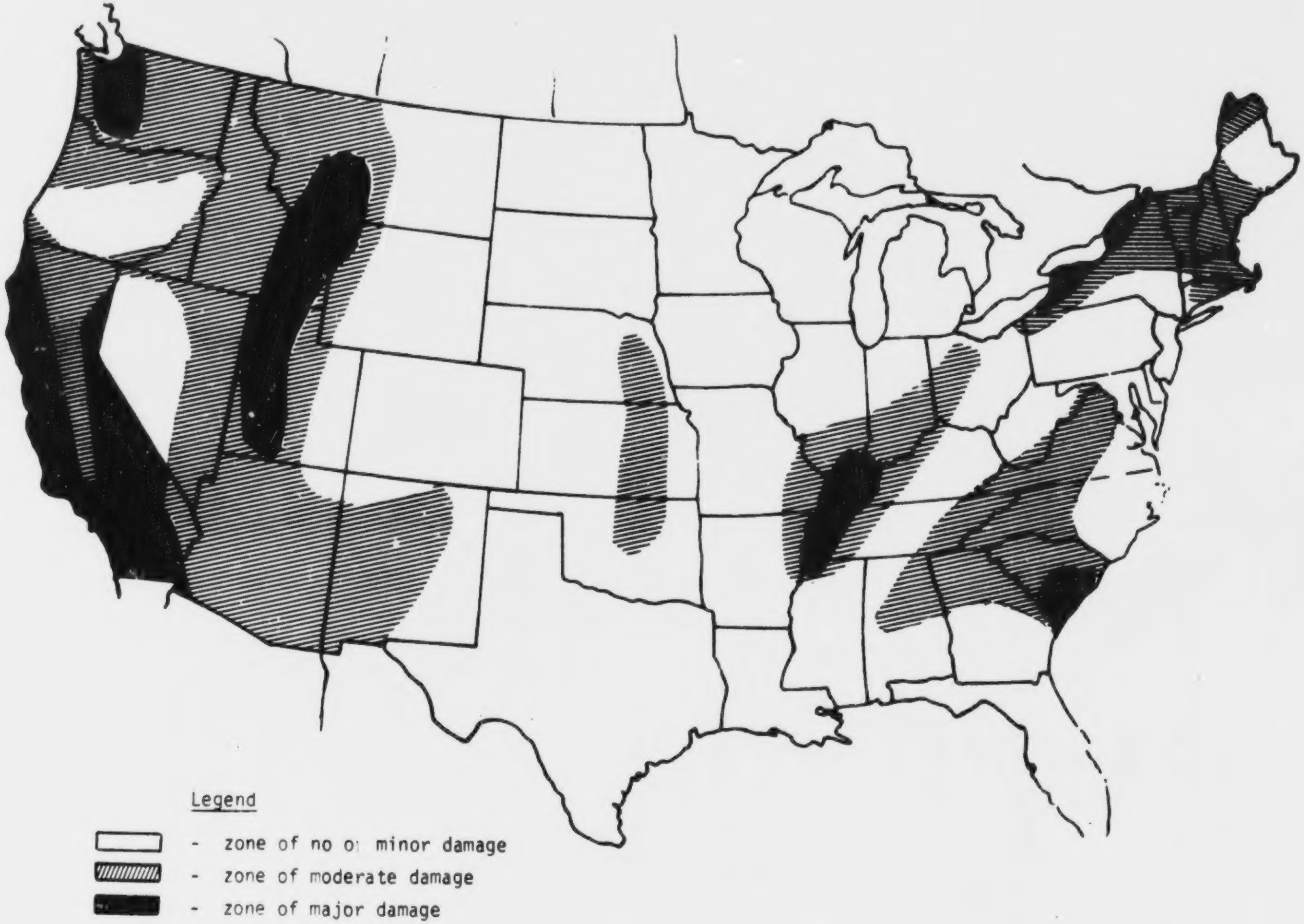

Legend
▭ - zone of no or minor damage
▨ - zone of moderate damage
■ - zone of major damage

Figure 1. Seismic Probability Map. 0705

Figure 2. The major areas with a population density of less than 30 persons per square mile are located in the midwest, southwest, and northwest regions of the United States. In addition to selecting an area of low population density the site should be located to minimize the distance required to transport the hazardous materials to the site.

Monitoring System

For each waste received at the burial site inventory records should be kept identifying the type of waste received, its activity and toxicity, and the source and quantity of the waste. Also the form (liquid or solid), type of container and date received should be recorded. A coding or permanent marking system should be devised to record the location of all buried wastes. These data should then be recorded on a map. A monitoring system is also required to measure the amount and location of any discharged wastes. This should include direct monitoring of the wastes in each burial site and monitoring of test wells, surfaces, streams, and lakes in the general area of the burial site.

In deep burial in either salt mines or hard bedrock a waste retrieval plan should be devised. This plan should call for the development of systems capable of retrieving the wastes. This plan should also be coupled with a worst case hazards analysis to determine what happens if the integrity of the site is destroyed or the waste retrieval system does not perform according to design. A continuous monitoring system is not only needed to measure the discharge of any wastes but to also measure any changes in the geology of the area and in the location of the buried wastes.

Present Design

At the present time most hazardous materials are disposed of by near-surface burial. These materials are either buried directly in the ground or in stainless steel tanks or concrete lined pits beneath the ground. Research and pilot plant studies are being conducted for deep burial in salt mines or hard bedrock.

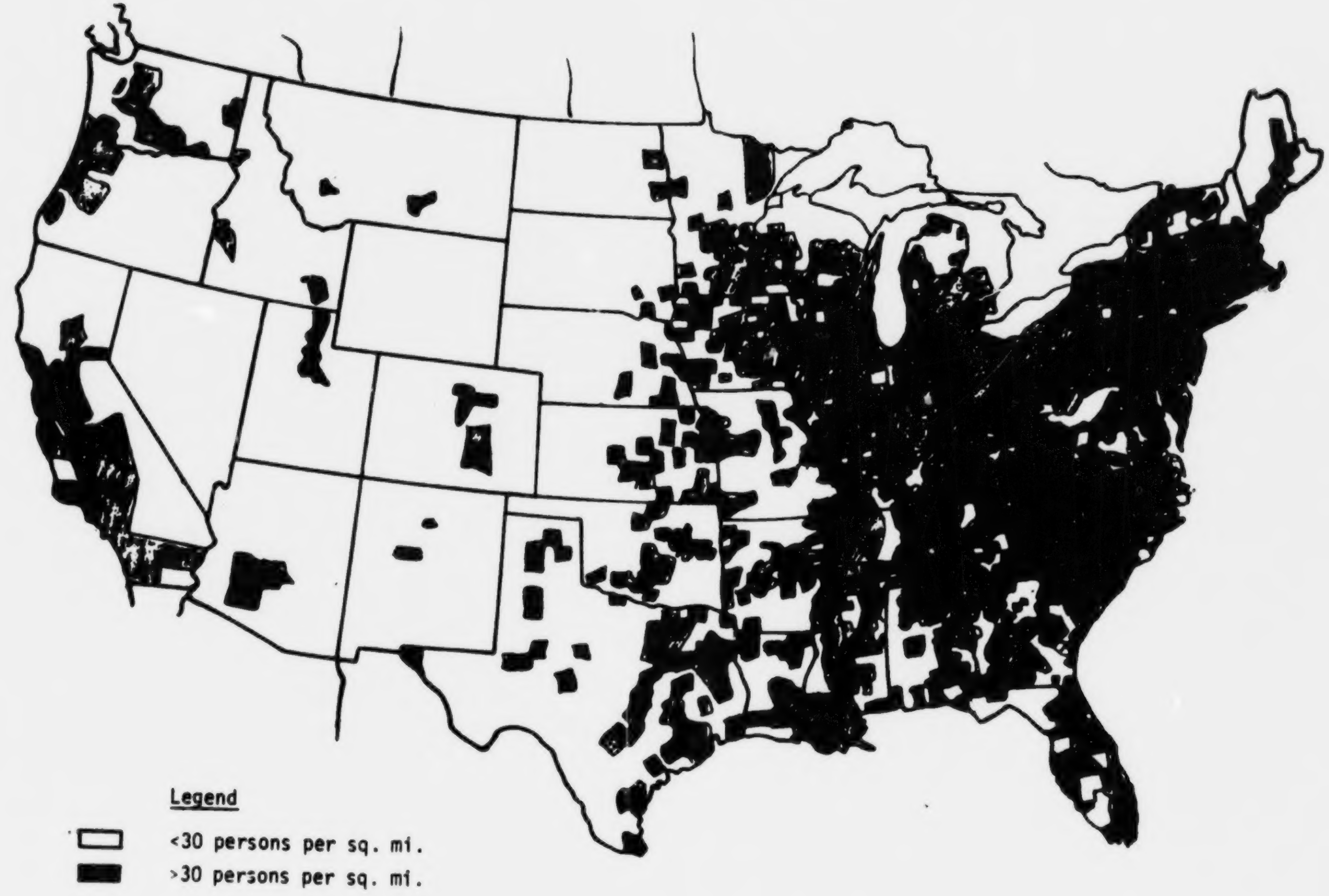

Legend
□ <30 persons per sq. mi.
■ >30 persons per sq. mi.

Figure 2. Population Density in the United States.[0705]

Near-surface burial of radioactive wastes is being conducted at several AEC sites and also at six commercial burial sites. The locations of these sites are included in this report (Tables 1 and 2). In addition to radioactive wastes some commercial burial sites also handle certain chemical wastes. These commercial burial sites are regulated by the AEC or by an AEC agreement state.

A complete description of the operation and facilities at several of the commercial burial sites is provided by R. J. Morton, AEC.[1423] A brief description of five of these sites is included (Table 3). At each of these sites the wastes are buried in trenches approximately 20 ft in depth. These trenches vary in width from 25 to 60 ft and vary in length from 300 to 700 ft. The design of the trenches at each site is fairly similar. The trenches are designed not to intercept the ground water table and are constructed with a bottom drain and sump for water monitoring. The trenches are unlined, so that the extent of leaching is dependent on the permeability of the soil. At each site liquid wastes are solidified by mixing with various additives, such as concrete, which absorb and solidify the wastes. These commercial facilities also offer packaging and transportation services.

Radioactive wastes have also been stored as liquids in stainless steel encased in concrete and buried underground. These tanks range in size from 0.33 to 1.3 million gal. The tanks are equipped with devices for measuring temperatures, liquid levels, leaks, and for agitating the contents. At the present time these tanks are considered as an interim storage technique due to a general lack of confidence in their long-term integrity.[0705]

Stainless steel bins buried beneath the ground have also been used at the Idaho Chemical Processing Plant, Idaho Falls, for solid radioactive wastes. The life of these bins has been estimated at 500 yr.[0710] The bins are constructed of 1/4-in.-thick stainless steel and each bin is 12 ft in diameter and 42 ft high. Six bins are enclosed in a concrete vault. The vault is constructed of two-ft-thick reinforced concrete and is 46 ft in diameter and 69 ft high. The vault is 45 ft below ground level and rests

TABLE 1

AEC BURIAL SITES

Site Designation	Contractors	Location
Hanford	Atlantic Richfield; Douglas	Richland, Washington
Savannah River	E.I. duPont de Nemours & Co.	Aiken, S. Carolina
National Reactor Testing Station	Argonne National Lab.; General Electric; Idaho Nuclear Corp.; Westinghouse	Idaho Falls, Idaho
Los Alamos	University of California	Los Alamos, New Mexico
Oak Ridge National Lab.	Union Carbide Corp.	Oak Ridge, Tennessee
Feed Materials Production Center	National Lead Co. of Ohio	Fernald, Ohio
Sandia Laboratories	Sandia Corporation	Albuquerque, New Mexico
Pantex Plant	Mason and Hanger-Silas Mason Co.	Amarillo, Texas
Nevada Test Site	Reynolds Electric and Engineering Co.	Mercury, Nevada
Paducah Gaseous Diffusion Plant	Union Carbide Corp.	Paducah, Kentucky
Portsmouth Gaseous Diffusion Plant	Goodyear Atomic Corp.	Piketon, Ohio

TABLE 2

COMMERCIAL BURIAL SITES

Location	Operator
West Valley, New York	Nuclear Fuel Services
Barnwell, South Carolina	Chemical Nuclear Service, Inc.
Beatty, Nevada	Nuclear Engineering Co.
Richland, Washington	Nuclear Engineering Co.
Sheffield, Illinois	Nuclear Engineering Co.
Morehead, Kentucky	Nuclear Engineering Co.

TABLE 3

COMMERCIAL RADIOACTIVE WASTE BURIAL SITE CHARACTERISTICS[1423]

Characteristics	Site
Background	**Beatty, Nevada**
Ownership of site	State of Nevada, leased to NECO
Population - density in area	Desert, virtually uninhabited
Location re towns and cities	About 12 mi southeast of Beatty
Area of (1) site; (2) control (acres)	(1) 80; (2) desert, not controlled
Communications	Good; hwy U.S. 95
Precipitation (in.)	2.5-5.0/yr
Site Characteristics	
Drainage	Adequate
Bedrock depth and materials (est)	575+ ft; various sedimentary and metamorphic
Surficial material - depth; types	$\sim$575 ft (?); alluvial clay, sand, etc.
Ground water - depth; slope	275-300 ft; SE $\sim$30 ft/mi
Land and water use downstream	Very little, desert conditions
General soil characteristics	Semi-arid desert; deep soil
Operation - Equipment and Methods	
Monitoring instruments and devices	14 survey instrs; film, air monitors; etc.
Waste handling machinery	Tank truck; trailer trucks; dozer; 35-T crane
Trenches - (1) dimensions; (2) design; (3) water pumped?	(1) 650 x 50 x depth 20 ft; (2) usual design, i.e., drain to sump, 4 ft backfill; (3) no water collected
Waste handling - (1) transport by company; (2) processing; (3) burial procedures	(1) yes; (2) liquids solidified; (3) sp. nu. mat. spaced at bottom, slit tr. for high-activity materials

TABLE 3

COMMERCIAL RADIOACTIVE WASTE BURIAL SITE CHARACTERISTICS[1423] Cont'd.

Characteristics	Site
Background	**West Valley, New York**
Ownership of site	NYASDA, leased to NFS
Population - density in area	Rural, less than 50/sq mi
Location re towns and cities	About 30 mi SW of Buffalo
Area of (1) site; (2) control (acres)	(1) 10+; (2) 3345 state owned
Communications	Good; U.S. hwy and rwy
Precipitation (in.)	40/yr
Site Characteristics	
Drainage	Several creeks
Bedrock depth and materials (est)	50-75 ft; type bedrock not stated
Surficial material - depth; types	25-35 ft glacial till; 25-35 ft silty till
Ground water - depth; slope	Variable; slopes with surface drainage
Land and water use downstream	Farming; no domestic surface supply
General soil characteristics	Slow water movement; good sorption
Operation - Equipment and Methods	
Monitoring instruments and devices	Variety, types, and numbers - as licensed
Waste handling machinery	Usual - crane, shovel, dozer, lifts, etc.
Trenches - (1) dimensions; (2) design; (3) water pumped?	(1) 700 x 35 x depth 20 ft; (2) usual design, bottom slope 2: 100; (3) yes
Waste handling - (1) transport by company; (2) processing; (3) burial procedures	(1) no; (2) no low-level processing; (3) usual, trenches filled, mounded cover

TABLE 3
COMMERCIAL RADIOACTIVE WASTE BURIAL SITE CHARACTERISTICS[1423] Cont'd.

Characteristics	Site
Background	**Morehead, Kentucky**
Ownership of site	State of Kentucky, leased to NECO
Population - density in area	Rural, sparse (Maxey Flats)
Location re towns and cities	10 mi northwest of Morehead
Area of (1) site; (2) control (acres)	(1) 200 (est); (2) 1000 (est)
Communications	Fair; state hwy N and S
Precipitation (in.)	46/yr (heavy storms)
Site Characteristics	
Drainage	Well drained
Bedrock depth and materials (est)	50-75 ft (?); shale, sandstone, siltstone
Surficial material - depth; types	50-75 ft (?) shale, clay, siltstone
Ground water - depth; slope	>320 ft ("perched" none); erratic
Land and water use downstream	Very little nearby, distant (no data)
General soil characteristics	Very impermeable; good soil sorption
Operation - Equipment and Methods	
Monitoring instruments and devices	Essentially same as at Beatty
Waste handling machinery	Usual - crane; dozer; forklifts; etc.
Trenches - (1) dimensions; (2) design; (3) water pumped?	(1) 300 x 50 x depth 20 ft; (2) usual design, sump; (3) Yes
Waste handling - (1) transport by company; (2) processing; (3) burial procedures	(1) and (2) same as Beatty (both NECO); (3) per "Radiation Safety Plan" (NECO)

TABLE 3
COMMERCIAL RADIOACTIVE WASTE BURIAL SITE CHARACTERISTICS [1423] Cont'd.

Characteristics	Site
Background	**Richland, Washington**
Ownership of site	State of Wash., leased to NECO
Population - density in area	No residents, inside AEC plant
Location re towns and cities	25 mi N of Richland
Area of (1) site; (2) control (acres)	(1) 100; (2) 1000 state owned
Communications	Good; AEC Hanford reservation
Precipitation (in.)	6-8/yr
Site Characteristics	
Drainage	Well drained
Bedrock depth and materials (est)	250-450 ft; basalt
Surficial material - depth; types	150-350 ft; silty sand, gravel, clay
Ground water - depth; slope	240 ft; N and E ∿ 15-35 ft/mi
Land and water use downstream	Columbia River - all uses
General soil characteristics	Little precipitation; deep dry soil
Operation - Equipment and Methods	
Monitoring instruments and devices	As licensed - survey instrs, film, counters
Waste handling machinery	Usual - crane, shovel, dozer, lifts, etc.
Trenches - (1) dimensions; (2) design; (3) water pumped?	(1) 300 x 60 x depth 25 ft; (2) usual design; (3) no water collects in sump
Waste handling - (1) transport by company; (2) processing; (3) burial procedures	(1) yes, 95%; (2) liquids solidified; (3) sp. nu. mat. spaced, separate trench for ion-exchange resins

TABLE 3
COMMERCIAL RADIOACTIVE WASTE BURIAL SITE CHARACTERISTICS[1423]

Characteristics	Site
	Sheffield, Illinois
Background	
Ownership of site	State of Illinois, leased to NECO
Population - density in area	Rural, sparse
Location re towns and cities	3 mi SW of Sheffield; others 3-7 mi
Area of (1) site; (2) control (acres)	(1) 27; (2) isolated, not controlled
Communications	Excellent, expressways and 2-lane hwy
Precipitation (in.)	35/yr
Site Characteristics	
Drainage	Intermittent drainage
Bedrock depth and materials (est)	40-60 ft; shale and clay, deeper is sandstone
Surficial material - depth; types	50-60 ft; glacial - silty clay, loess
Ground water - depth; slope	40-60 ft (SW), 15-25 ft (N); N ~ 100-150 ft/mi
Land and water use downstream	No specific information; probably limited
General soil characteristics	Low permeabilities; some shallow soil cover
Operation - Equipment and Methods	
Monitoring instruments and devices	Survey instrs; monitoring system and lab
Waste handling machinery	Usual - lifts, dozer, crane, etc.; medium cap
Trenches - (1) dimensions; (2) design; (3) water pumped?	(1) 500 x 40 x depth 20 ft; (2) usual, drain and sump; (3) no
Waste handling - (1) transport by company; (2) processing; (3) burial procedures	(1) yes; (2) liquids solidified - vermiculite and cement; (3) usual, per regulation

on bedrock. The vault is provided with a cooling air system to provide convective cooling of the bins. A detailed design of these storage facilities is available.[0710]

Pilot plant studies have been conducted for deep burial in salt mines. Detailed designs of a salt mine disposal facility for solid radioactive wastes[0696] and for solid chemical wastes[0957] have been prepared. At the salt disposal facility the wastes would be received at a surface facility and lowered down a steel-lined shaft into the working area of the mine. The working area would be located approximately 1,000 ft below the surface. The wastes would then be transported to the disposal area in the mine by either a specially designed underground waste transporter or by a conveyor belt. After the waste disposal operations are complete in a particular area, this area is then shut off by backfilling with salt.

Studies have been conducted at the Savannah River Plant[0738] near Aiken, South Carolina for the disposal of radioactive wastes in vaults excavated in crystalline rock 1,500 ft beneath the surface. Access to the vault would be provided by a 15-ft-diameter shaft. The wastes would be stored in tunnels extending from the central shaft. These tunnels would be approximately 30 ft wide and 18 ft high. Each tunnel is provided with a 2-ft-diameter service shaft. For the disposal of liquid wastes the tunnel is isolated from the main shaft by two concrete bulkheads, each 10 ft thick. The tunnel is then filled via the main shaft with the service shaft serving as an air vent. After the tunnel is filled, it is sealed by two concrete bulkheads.

4. PROCESS ECONOMICS

Typical rates charged at the six commercial burial sites for near-surface burial of radioactive or chemical wastes are included (Table 4). The wastes received at each burial site must be enclosed within containers that are in accordance with AEC, U. S. Department of Transportation (DOT), or U. S. Bureau of Explosives regulations. The minimum rate charged for unloading and burying these containers is $0.75 per cubic foot. Special surcharges are also made for containers weighing in excess of 15 tons

TABLE 4

TYPICAL RATES CHARGED AT COMMERCIAL BURIAL SITES[1423]

Basic rate for containers less than 15 tons total weight: $0.70 per cubic foot plus state charge of $0.05 per cubic foot.

Surcharge for containers in excess of 15 tons:

	Surcharges ($)	
Weight, Tons	Per Shipment	Per Container
0 - 15	0.00 plus	0.00
15 - 30	130.00 plus	200.00
30 - 50	260.00 plus	330.00
50 - 60	520.00 plus	475.00
60 - 80	1,600.00 plus	1,200.00
80 - 130	3,200.00 plus	2,500.00

Surcharge for special handling of containers consisting of two or more parts. This is for removing and burying inner containers which have been shipped inside a shielded coffin, cask or container:

Primary Containers with Surface Dose Rates	$ Per Shipment		$ Per Hour*
0.2 to 10 r/hr	$ 25.00	plus	$26.00
10 to 50 r/hr	50.00	plus	26.00
50 to 100 r/hr	100.00	plus	26.00
100 to 500 r/hr	250.00	plus	26.00

*The $26.00 per hour referred to includes consulting and preparation of proper procedures.

Minimum charge for any shipment is $20.00.

and for containers that require special handling.

Cost studies have been conducted[0705] for tank storage of radioactive wastes. The waste management and storage costs were based on an economics model using a discounted cash flow technique. This type of model requires that the income received must provide for the recovery of investment, the desired return on investment, all cash expenses, and the establishment of a reserve account to pay all waste management operations that remain to be completed after all income has ceased. Using this model, costs were determined[0705] for perpetual tank storage of high-level liquid radioactive wastes. For a 50-yr tank life and a 1,000,000 gal. capacity the costs varied from $4,100 to $8,200 per ton of fuel depending on the type of waste (acid or alkaline) and type of ownership (government or private). Costs for interim solid storage of radioactive wastes in water-filled canals were presented as a function of age of the waste. The costs range from $1,275 per ton of fuel for 1 yr storage of 30-yr-old waste in 6-in.-diameter pots to $4,100 per ton of fuel for 30 yr storage of 1-yr-old waste. Costs were also presented for solidifying these wastes using the pot calcination technique. For calcination in 6-in.-diameter pots these costs ranged from $4,200 per ton of fuel for 1-yr-old waste to $800 per ton of fuel for 30-yr-old waste.

For deep burial of hazardous materials in salt mines cost studies[0696,0705] for radioactive wastes and for chemical wastes[0957] are included. For radioactive wastes the costs were based on the same economic model described above. The wastes were assumed to be buried in vertical holes in the floor of the salt mine at a depth of 1,000 ft. The burial costs vary with the heat generation rate and age of the waste at burial. For burial in 6-in.-diameter pots the disposal costs range from $2,800 per ton of fuel for 1-yr-old waste to $260 per ton of fuel for 30-yr-old waste.

Detailed cost estimates for constructing and operating a chemical waste storage facility in bedded salt have been derived.[0957] The facility was located in Boco County, Colorado and had a storage space of 43.6 million cubic ft mined in bedded salt at a depth of 1,330 ft. The total cost of the facility was estimated at $41 million which gives an average cost of $0.96 per cubic foot of waste stored. Cost for disposal in a solution mined facility were also presented. This facility would consist of four caverns having an average diameter of 67 ft and a height of 4,000 ft. The total volume of the four caverns would be 43.6 million cubic ft and the average cost of disposal was estimated at $0.32 per cubic foot of waste stored.

5. PROCESS APPLICABILITY

Land burial is a possible choice for those hazardous materials that require complete containment and permanent disposal. This includes radioactive wastes as well as highly toxic chemical wastes. Disposal can be accomplished by either near-surface or deep burial. Deep burial is more applicable to the highly toxic or dangerous materials since better isolation from the biosphere is afforded. The important criterion in evaluating a particular land burial process is determining the integrity of the site. Sites with a life expectancy of a few hundred years are not applicable to wastes with a life expectancy of a few thousand years. In addition, before any land disposal methods can be selected, it must be determined if eventual retrieval of the wastes is required. This could be required if new reprocessing techniques are devised or under emergency conditions.

At the present time only near-surface burial is used for the disposal of most wastes. Low-level radioactive wastes and some chemical wastes are buried in unlined trenches 20 ft in depth. High-level radioactive wastes are stored as liquid in steel tanks located near the ground surface. For deep burial in salt formations or hard bedrock only pilot plant studies are being conducted at the present time.

6. REFERENCES

0696. Bradshaw, R. L. et al. Evaluation of ultimate disposal methods for liquids and solid radioactive wastes VI disposal of solid wastes in salt formations. Oak Ridge National Laboratory, ORNL-3358. Mar. 1969.

0705. Staff of the Oak Ridge National Laboratory. Siting of fuel reprocessing plants and waste management facilities. Oak Ridge National Laboratory, ORNL-4451, July 1970.

0710. Bendixsen, C. L. Storage facilities for radioactive calcined waste solids at the Idaho Chemical Processing Plant. Idaho Nuclear Corp., Idaho Falls, IN-1155. July 1968.

0738. Proceedings of the Symposium on the Solidification and Long-Term Storage of Highly Radioactive Wastes, sponsored by Atomic Energy Commission, Richland, Washington, Feb. 14-18, 1966. CONF-660208.

0957. Dunn, C. S. et al. Feasibility of permanent storage of solid chemical waste in subsurface salt deposits. Fenix and Scission, Inc., Tulsa, Oklahoma, F&S-196, Oct. 1971.

1423. Morton, R. J. Land burial of solid radioactive wastes: study of commercial operations and facilities. Atomic Energy Commission, Washington, WASH-1143, 1968.

LANDFILL DISPOSAL

1. INTRODUCTION

Wastes received at a hazardous waste disposal facility or generated as the residue from other neutralization/detoxification processes can be solids, liquids, sludges or slurries, or combinations thereof. Common landfill disposal methods for these materials include the following: (1) mixing with soil, (2) evaporation and infiltration, and/or (3) shallow burial.

Combinations of these methods can be involved in a disposal process. For example, in the spreading of a slurry on land, the liquid content may either evaporate or infiltrate into the subsoil. Solid wastes will normally be incorporated in a landfill and buried. Liquids, slurries, and sludges might also be incorporated into a landfill; however, due to the large quantity of moisture contained in these wastes, disposal practices usually involve spreading them on land or placing them in ponds to maximize evaporation or infiltration.

2. OPERATION PRINCIPLES

Landfills operate on two principles: (1) utilization of the absorptive capacity of the soil and, perhaps, some biological degradation of the wastes by soil microorganisms; and (2) storage of wastes such that they are isolated from direct contact with man and the surface environment. Some liquid wastes are currently discharged to infiltrate and percolate into the underlying porous sediments where there is no possibility of ground waste impairment. In other cases simple, shallow burial of solid wastes in a geologically "dead" area is the ultimate method of disposal. It must be stressed that the usability of any landfill site is basically determined by the site's characteristics and that their investigation is of utmost importance to site selection.

3. DESIGN

Climatological, Demographic, and Geological Investigations

As part of the selection investigations of a proposed hazardous waste disposal site the basic meteorology of the site must be investigated. The two primary elements of this investigation are the determination of the average rainfall in the area and the construction (from available historical data) of a wind rose for the site.[0230]

Demographic data for the area consists of a plot of the population distribution within a 25-mile radius of the site which can be compared with the direction of the prevailing winds.

The geological and ground water conditions should be investigated through a program of field inspection and testing that involve soil and rock examination and the boring of test holes.[1509] The investigation should study the depth and occurrence of ground water, its natural quality, and the existence of natural impervious barriers. The soil types, permeability, depth and thickness of impervious layers, extensiveness of their lateral continuity, and occurrence of dip and strike of the layers should also be determined. The investigation should indicate either that geologic and hyrologic conditions will prevent migration of hazardous material onto adjacent properties or that appropriate design features are feasible to preclude such migration. Hydrogeologic conditions of the disposal facility should be described in the report.

The number of test holes required to indicate underlying geologic conditions should be related to the adequacy of detailed information from other sources. Information should be provided on underlying geology to confirm rock types and ground water conditions (absence of ground water and/or its occurrence and quality). Shallow zone exploration should involve drilling a minimum of three test holes on the site to a depth determined by the geologist in charge of the investigation. More test holes may be necessary depending on the size of the property and the potential for variable geologic conditions. A rough guideline is one test hole per each five acres of the actual area to be used for waste disposal. Drilling logs should be included in the report for the test holes and any wells constructed.

The area used for any hazardous waste disposal facility should be free from potential geological hazards, such as known earthquake faults and land slippage or slide zones. In areas of major subsidence, this hazard should also be evaluated. Land slippage or settlement can result in rupture of levees surrounding industrial waste ponds, exposure of buried hazardous materials, or slippage of earth masses into large ponds which can result in liquids breeching or overtopping pond walls. The effect of waste liquids percolating through soils on slope or levee stability of other zones of weakness must be considered in the design of waste disposal areas.

If the method of operation relies on the infiltration of large quantities of liquids, the natural soils on the property should be relatively permeable to allow infiltration to occur, and sufficient subsurface storage capacity for the liquids should exist. Conversely, if impervious basins are desired and the native soils are not suitable for that purpose, impermeable materials may have to be imported or artificial linings installed.

Soil and rock types should also be suitable for the type of excavation work anticipated. Excavations made to allow location of the disposal facility should not create hazards of slope instability or problems of erosion. The degree of slopes should be consistent with good engineering practice for the particular soil or rock type. Erosive soils should be protected such as by use of mulches or hydroseed applications.

Finally, if artificial barriers are to be installed, a report should be submitted indicating the long-term competence of such a barrier. Response to seismic activity and possibility of destruction through shrinking and cracking due to drying or action of the hazardous wastes should be evaluated. Pre-tests should be made on all prospective liners to determine compatibility with the material being disposed.

Qualitative Evaluation of Landfills

The parameters resulting from the investigation of potential sites outlined above must be compared against standards designed to protect man and the environment from the hazards associated with the various wastes. In California a set of standards for selecting landfill sites which is based on contamination of usable water supplies has been defined and used by the State Department of Public Health, the Department of Water Resources, and the various California Regional Water Quality Control Boards. According to a paper by Lawrence A. Burch of the State Department of Health[2610] three classes of wastes are recognized as requiring distinct levels of control of site effluents (surface or subsurface): (1) water soluble materials that constitute hazards of high toxicity or special water pollution potential; (2) decomposable organic materials; and (3) relatively inert, non-decomposable materials. Correspondingly, three classes of landfills disposal sites are recognized and are described by Burch as follows:

"Class 1 sites are those sites located over nonwater-bearing sediments or with only unusable ground water underlying them. The site location must provide complete protection from flooding, surface runoff or drainage, and waste materials and all internal drainage must be restricted to the site. In essence, a Class 1 site is a large container providing safe, ultimate storage of toxic or hazardous materials; a secondary function of the site might be the processing of the waste such as evaporation to reduce the volume of the material to be disposed of. These sites can accept almost any type of materials, liquid or solid. These are the only sites where the first group of wastes, such as toxic materials, oily sludges and soluble industrial chemicals may be placed. It should be noted that possible public health hazards must be recognized at the Class 1 sites in addition to water quality protection. Certain very toxic chemicals such as pesticides or tetraethyl lead may require special handling techniques to protect site personnel and to provide long-term protection of public health and the environment.

"Class 2 sites are underlain by usable ground water and may be located adjacent to streams. To protect the underlying ground water quality, a distance of separation must be maintained between the bottom of the fill and the water table. Any surface water must also be restricted from the site to preclude water from contacting the wastes. The second group of wastes (decomposable materials such as refuse) is the acceptable material at this class of site, along with the third group materials.

"Class 3 sites are those sites which intercept ground water or where wastes will be dumped directly into water. Examples are deep gravel pits with ground water ponded in the bottom and swampy areas where filling operations commence without construction of levees and removal of the water. Only the third group of wastes is allowed to be disposed of in this class of site. These nonwater soluble, nondecomposable inert materials such as concrete and bricks will not adversely affect the quality of water that they may contact."

This type of classification together with geologic consideration such as faults location, etc., described earlier is necessary for proper management of wastes.

Quantitative Evaluation of Landfills

The procedures outlined above are all necessary to the proper selection of a site utilizing Landfill Disposal. The data provided by the various procedures includes both quantitative and qualitative information, but the evaluation of these parameters is currently handled on a totally subjective basis such as that outlined above. This subjective evaluation does not provide the necessary methodology for comparing one site with another or for determining absolute suitability of a site for a particular waste material. A methodology providing the framework for quantitative evaluation has been proposed by Pavoni, Hagerty, and Lee[0230] and is described in the Appendix. Considerable research is required to test and revise the quantification, but such methodology is necessary to ensuring that factors other than economics will receive consideration in site selection.

4. PROCESS ECONOMICS

The operating cost of a sanitary landfill depends of the cost of labor and equipment, the method of operation, and the efficiency of the operation. The principal items in operating cost are:[0772]

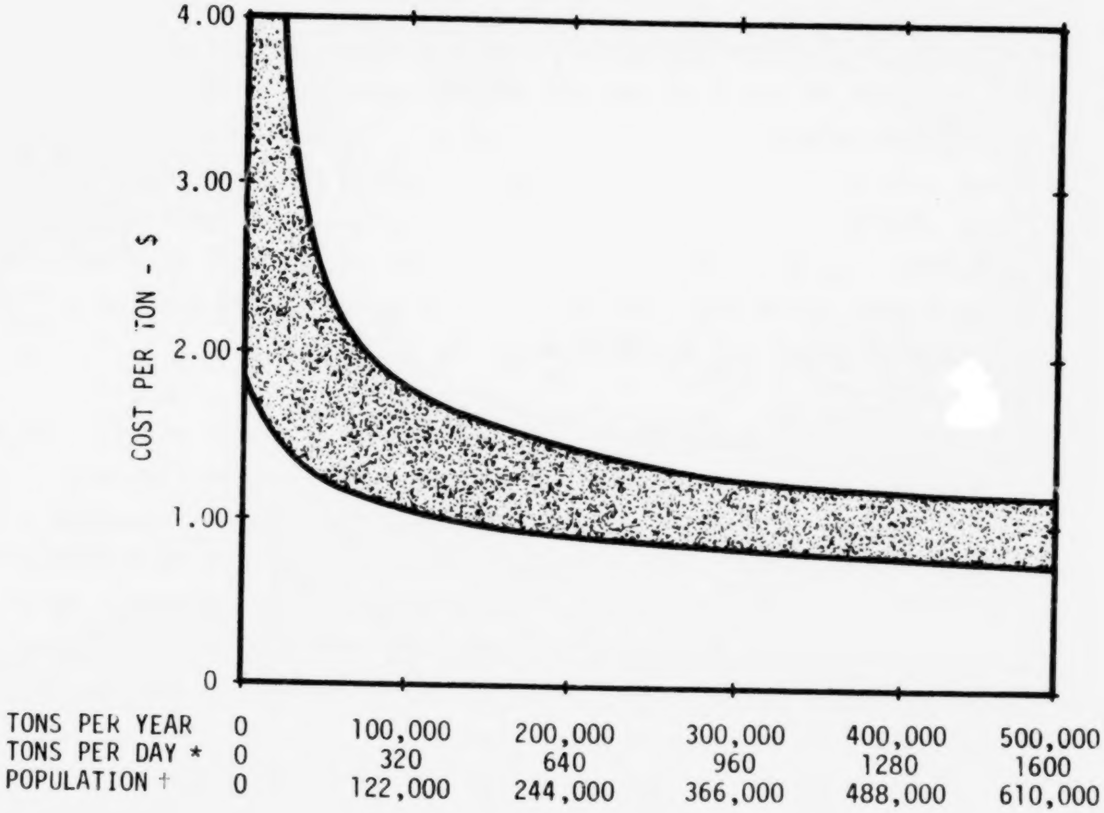
(1) Personnel
(2) Equipment
    Operating expenses - gas, oil, etc.
    Maintenance and repair
    Rental, depreciation, or amortization
(3) Cover material - material and haul costs
(4) Administration and overhead
(5) Miscellaneous tools, utilities, insurance, maintenance to roads, fences, facilities, drainage, features, etc.

Wages ordinarily make up about 40 to 50 percent; cover material, administration, overhead, and miscellaneous amount to about 20 percent.

The operating costs per ton versus the amount of solid wastes handled in tons and the population equivalent may be charted (Figure 1).

The operating cost of a small operation handling less than 50,000 tons per year varies from $1.25 to approximately $5.00 per ton. This wide range is primarily due to the low efficiency of the smaller operations which are usually operated on a part-time basis.

Full-time personnel, full-time use of equipment, specialized equipment, better management, and other factors that lead to high efficiency are possible at large sanitary landfill operations. The increased efficiency results in lower unit cost of disposal. The unit cost of a large landfill handling more than 50,000 tons per year will generally fall between $0.75 to $2.00 per ton.



* BASED ON 6-DAY WORK WEEK.

† BASED ON NATIONAL AVERAGE OF 4.5 LBS PER PERSON PER CALENDAR DAY.

Figure 1. Sanitary Landfill Operating Costs

5. APPLICABILITY OF PROCESS

The utilization of landfill procedures for the disposal of certain hazardous waste materials at a National Disposal Site, in an industrial environment, or in municipal application will undoubtably be required in the future. In order to ensure that no damage to man or the environment results from this technique it is recommended that all sites currently used or proposed for the landfill disposal of hazardous wastes be subjected to the design procedures specified in Section 3. It is further recommended that any site considered as a National Disposal Site be subjected to the analyses whether it is expected that landfill will be a primary disposal mode at that site or not since account must also be taken of possible accidental spillage of materials which represents an unintentional but direct application of the landfill technique.

The waste stream constituents considered in the context of this program are primarily in the category described in Section 3 as Class 1. It is therefore recommended that any disposal facility handling these materials be required to meet the Class 1 site criteria as specified in the Section 3 discussion. Finally, it is recommended that the landfill disposal model described by Pavoni, Hagerty, and Lee, and presented in the Appendix to this Process Description be tested, modified, and applied to provide the best possible sites for all types of landfill disposal.

APPENDIX

Landfill Site Numerical Evaluation

In order to evaluate the potential danger of depositing any hazardous material in a particular landfill site it is necessary to critically examine three general characteristics of that site: (1) the potential for precipitated surface waters to infiltrate the deposited waste material; (2) the potential for the waste material to be transported through fluid transmission from its deposit location through underlying bottom soils to groundwater systems; and (3) other mechanisms for the removal of hazardous materials from the site and their transport to other areas. A number of factors have been included quantitatively in the site rating procedure originally presented by Pavoni, Hagerty, and Lee[0230] which follows:

Soil Parameters

"Infiltration Potential - The potential for water to enter a waste deposit may be quantitatively expressed as the ratio of the amount of water which may enter the top surface of the cover soil divided by the amount of water necessary within the cover soil to produce a full passage of moisture from the top of the layer to the bottom of the layer and out into the contained refuse. The amount of water (i) which could theoretically enter the site or enter the cover soil at the site may be estimated as the total area under all of the rainfall intensity graphs for the site, beneath a horizontal line representing the infiltration rate of the cover soil (see Figure 2). The infiltration rate of the cover soil may be expected to vary from 0.01 in/hr for bare heavy clay soils to approximately 3 in/hr for loose sands. The probable range of (i) will be from 1 to 64 in.

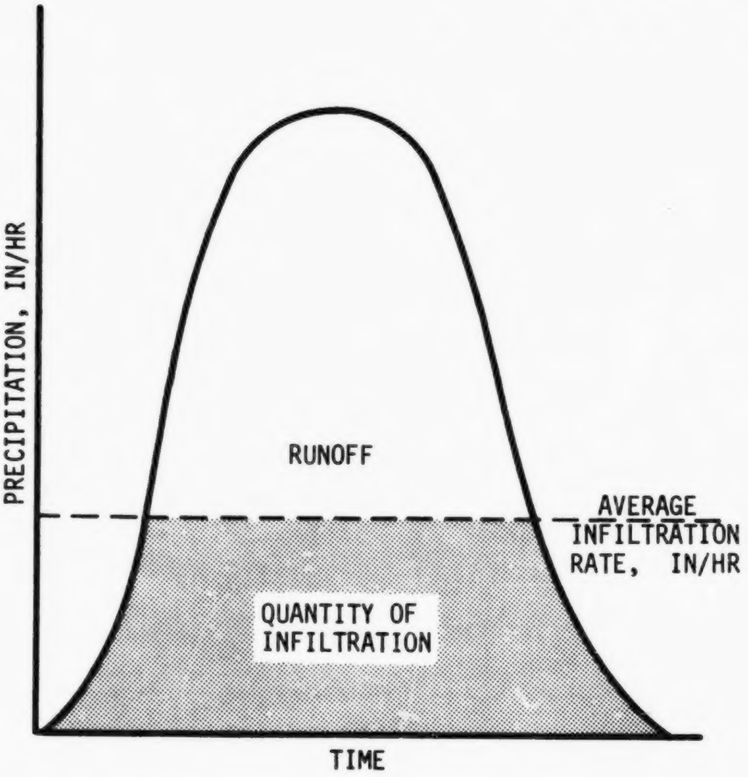


Figure 2. Precipitation/Infiltration Chart

The amounts of water necessary for passage of moisture through the cover soil layer may be related to the volumetric field capacity of the cover soil layer. In other words, whereas the field capacity refers to the amount of water as a percentage of the dry unit weight of the soil required for passage of water through a unit volume, the volumetric field capacity in this instance would refer to the product of the thickness of the cover soil layer times the field capacity of the soil. Thus, let FC(H) be the denominator of the infiltration potential term.

where FC = field capacity of the soil expressed as a decimal
and H = thickness of cover soil layers (inches)

The field capacity will vary from .05 for a clean sand to .40 for a clay, whereas H will vary from approximately 30 inches to 72 inches. The infiltration potential may be finally quantitated as:

$$Ip = \frac{2i}{(FC)\ H}$$

having a practical range of 0.02 to 20. This infiltration potential may be thought of as one of the most significant factors in determining the site potential for waste transmission.

Bottom Leakage Potential - In addition to the problem of water entering the refuse cells and removing the contained hazardous material, consideration must be given to the action of a waste in suspension or solution in water, or in liquid form, passing through the bottom soil layer from its original location and entering the groundwater system.

The potential hazard for a waste to travel through a bottom soil from the bottom of the refuse cell through the containing soil layer and into a groundwater flow system may be evaluated in terms of the permeability of the bottom soil layer and its thickness. Since all natural geological materials possess some finite permeability it is fatuous to think in terms of an impermeable bottom in a landfill. Even in the situation where an artificial lining material has been applied to the bottom of a refuse cell, it is quite probable that the artificial liner is in truth not impermeable.

For example, thin sheets of impervious polyvinyl chloride or polyethylene lining may easily be pierced and penetrated during placement or after placement by sharp-edged equipment or refuse items. Asphaltic liners likewise may crack because of distortions experienced when the bottom soils settle as a result of the applied loads of the landfill. Thus, in all cases, a certain finite permeability of the bottom confining layer must be anticipated. Therefore, in a true sense, the migration of materials from the landfill site into the substrate must always be anticipated and the only variable to consider is the time which will be required for such migration; in other words, the migration time for a hazardous substance through a bottom soil layer consisting of clay minerals may be sufficiently long so that the substance's half life is greatly exceeded. In such a case the virulence and hazardous nature of these substances will be diminished.

For this reason this bottom leakage factor has been quite simply expressed in the form shown below to give a measure of the time factor for migration of a hazardous material in terms of permeability and thickness of the bottom soils.

$$\text{Bottom Leakage Potential (Lp)} = \frac{1000\ \sqrt[3]{K}}{T}$$

where K = bottom soil permeability (cm/sec)
T = bottom soil thickness (ft)

The approximate range for K for all practical problems will be about 10^{-1} to 10^{-10} cm/sec, whereas T will vary from 5 to 50 feet. The overall range of Lp will therefore be from approximately 0.02 to 20.

Filtering Capacity - A less important characteristic of the bottom soils will be their ability to remove solid particles traveling downward (through the bottom soil layer) in a fluid suspension. In general, this filtering capacity is dependent upon the sizes of the pore spaces between individual soil grains. In other words, the physical filtering ability of the bottom soil will depend upon void-space size in that soil and may therefore be related to the size of the soil particles themselves. The physical filtering capacity may be considered proportional to the inverse of the average grain size in the soil stratum. Therefore, the filtering capacity of the bottom soil layer may be easily expressed as shown below.

$$\text{Filtering capacity (Fc)} = \frac{-8.75}{\log \phi}$$

where ϕ = average particle diameter (inches)

The average particle diameter of various soils will vary from about 0.25 to 2.5×10^{-5} inches. Therefore the "filtering capacity" will vary between approximately 2.1 and 15.0.

Adsorptive Capacities - In addition to the removal of solid particles through physical filtering within the bottom soil layer, certain materials will be removed from suspension and solution in a migrating fluid by the physical-chemical attraction of the mineral constituents within the soils. Adsorption of materials both organic and inorganic in the migrating fluids will take place principally on colloidal-size particles consisting of clay minerals which describe the attracting of such minerals for the migrating particles. A general measure of such attraction is the cation exchange capacity of the clay mineral. In this rating system the greater the danger of transmission of a hazardous material from a landfill site the greater the rating factor; therefore, the greater the ability of the bottom soil layer to adsorb migrating materials the smaller should be the adsorption factor. The ability of the soil is evaluated as an inverse quantity and a factor is obtained by dividing a numerator by cation exchange capacity in the denominator. The cation exchange capacity alone will not reflect the potential for adsorption of a material on the minerals present in the soil. If the available adsorption positions on the soil mineral are already occupied then no further adsorption can occur. The occupancy of the adsorption sites in the soil are already occupied by organic compounds and complex organic ions. Therefore, the complete adsorptive capacity factor will consist of the organic content as the numerator and the cation exchange capacity as the denominator as follows:

$$\text{Adsorptive capacity (Ac)} = \frac{10\ (o)}{(\log \text{CEC}) + 1}$$

where o = organic content expressed as a decimal

CEC = cation exchange capacity, me/100g

The range in the numerator will therefore be from 0 to 10, whereas the log CEC will range between about 0.6 to 2.2. The adsorptive capacity (Ac) will therefore vary between approximately 0 and 16.

Groundwater Parameters

Organic Content - Transmutations of a hazardous material following contact with groundwater must also be evaluated. Assuming that a hazardous waste has reached the groundwater after disposal in a landfill, probably the most important single water parameter to be considered would be that of organic carbon content. The organic content of the groundwater may be quantitated in terms of the biochemical oxygen demand or BOD. The higher the organic content (BOD) of a groundwater, the higher the substrate potential, and consequently the higher the potential it may afford pathogenic organisms.

Groundwater organic content was assigned a third order of priority with regard to landfill ranking factors so that its range of values was fixed between 0 and 10 dependent upon BOD values as follows:

$$\text{Oc} = .2\ \text{BOD}$$

where Oc = organic content rating (maximum value of 10)

BOD = biochemical oxygen demand of groundwater (mg/l)

Buffering Capacity - The buffering capacity of a groundwater is another important parameter when considering transmutations of hazardous wastes in groundwater systems. Any waste material having acidic or alkaline characteristics would be less hazardous to the groundwater ecosystem if the water it is entering possesses a high buffering capacity. In other words acidic or basic waste characteristics would be neutralized or moderated upon contact with a high buffering capacity water system.

Groundwater buffering capacity was assigned a third order of priority and was quantitated in relation to pH, acidity, and alkalinity. For the purposes of this study the buffering capacity ranking (Bc) will be equal to ten minus the smallest number of milliequivalents (maximum of ten) of either an acid or base required to displace the original groundwater pH below 4.5 or above 8.5. The buffering capacity ranking will therefore vary from 0 for a strong buffer to 10 for a weak buffer.

Potential Travel Distance - The potential for travel of a hazardous waste once it enters a groundwater system will determine how much of the immediate landfill environment it may affect. This potential travel distance was assigned a fourth order of priority and varied in value from 0 to 5 depending upon the greatest possible distance a molecule of water could travel from a point directly beneath the landfill through the groundwater system and surface water systems, and thence to the sea.

Potential Travel Distance	Travel Distance Ranking (Td)
0 to 500 ft	0
500 to 4000 ft	1
4000 ft to 2 miles	2
2 miles to 20 miles	3
20 miles to 50 miles	4
Greater than 50 miles	5

Ground Water Velocity - The groundwater velocity will determine how fast a hazardous material may spread into the environment. A groundwater system having a high velocity should therefore be assigned a higher ranking since the time of waste transmission would be reduced.

The groundwater velocity, having a fourth order of priority, may be defined as:

$$v = kS$$

where V = velocity
k = permeability
S = gradient

Values of k will vary between 10^{-1} and 10^{-9} cm/sec whereas values of S will usually range between 0 and 20 ft/mile. Groundwater velocities were ranked according to the following formulation:

$$Gv = \frac{S}{\log\left(\frac{1}{k} + 1\right)}$$

where Gv = groundwater velocity rank
k = permeability (cm/sec)
S = gradient (ft/mile)

The groundwater velocity rank will approximately range between 0 and 20.

Air Parameters

Prevailing Wind Direction - The third major site characteristic to be investigated is air. The hazardous potential of any toxin or pathogen escaping through the atmosphere from the landfill would depend upon the prevailing wind direction in relation to the distribution of population surrounding the site. Obviously the worst situation would be one in which a strong prevailing wind blew from the site to the center of a very dense population.

The following procedure was therefore developed to quantitatively evaluate the potential of the prevailing wind direction. Initially, a twenty-five mile radius circle was constructed with the landfill site as its center (see Figure 1). This circle was then divided into four quadrants by drawing two lines - one north-south, and one east-west. The population of each quadrant was determined (Pi) and a point representing the center of population (population node) was located in all four quadrants (PNi). A radius was then drawn from the site to each quadrant's population node. The prevailing wind direction was determined and a

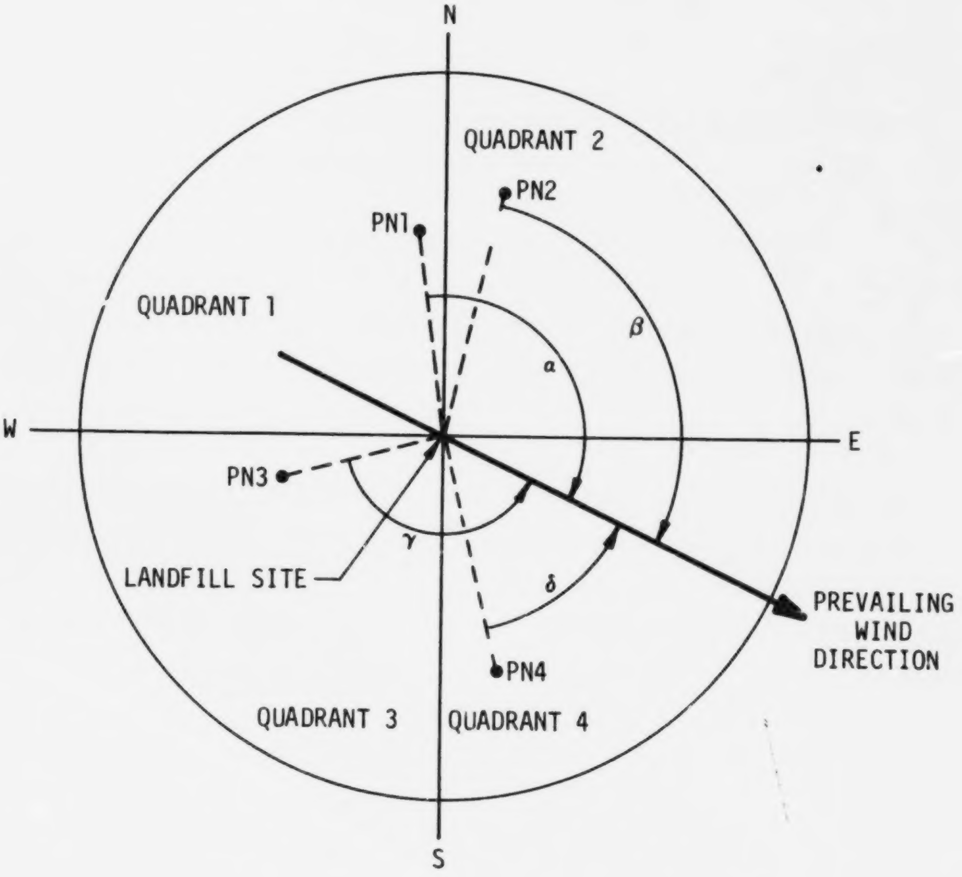

N
QUADRANT 2
PN2
PN1
QUADRANT 1
β
α
W
E
PN3
γ
LANDFILL SITE
δ
PREVAILING
WIND
DIRECTION
PN4
QUADRANT 3
QUADRANT 4
S

Figure 3. Prevailing Wind Rose[0230]

radius drawn in this direction from the site (center of circle). The angles from the prevailing wind direction to each site-population node radius were determined (α, β, γ, δ) and incorporated in the following prevailing wind potential formula:

$$Wp = \sum_{i+1}^{4} \frac{[(5 - \frac{Ai}{36}) \log Pi]}{15}$$

where Wp = prevailing wind potential rank

Ai = the angle from the prevailing wind direction to each site-population node

Pi = the population of each quadrant

Wp quantitatively interrelates the prevailing wind direction, site location, and population nodes of each quadrant. Wp has a practical range of 0 to 5.

Population Factor - The population immediately surrounding the landfill site will determine how many persons could be adversely affected by escaping hazardous materials. The higher the population within a specified radius of the landfill site the higher the population factor ranking as shown:

$$Pf = \log p$$

where Pf = population factor rank

p = population within a twenty-five mile radius of the landfill site

The population factor rank will range between 0 and 7.

The total landfill site ranking formula may not be assembled by uniting the various soil, water, and air parameters as follows:

$$\text{Landfill Site Rank} = Ip+Lp+Fc+Ac+Oc+Bc+Td+Gv+Wp+Pf$$

where Ip = Infiltration Potential

Lp = Bottom Leakage Potential

Fc = Filtering Capacity

Ac = Adsorptive Capacity
Oc = Organic Content
Bc = Buffering Capacity
Td = Potential Travel Distance
Gv = Groundwater Velocity
Wp = Prevailing Wind Direction
Pf = Population Factor

The first four parameters (Ip,Lp,Fc, and Ac) describe the soil system, the next four factors (Oc,Bc,Td, and Gv) delineate the groundwater characteristics, and the last two terms (Wp and Pf) depict air parameters. The total landfill rank may assume values from approximately 0 to 110, the lower the rank the better the landfill for hazardous waste disposal.

The following data has been accumulated concerning two existing landfill sites in Louisville, Kentucky so that a ranking comparison can be developed.

	Site #1	Site #2
Yearly rainfall	43 in.	43 in.
Soil type	clean sand	heavy clay
Infiltration rate (% of rainfall)	75	10
Field capacity	.05	.40
Permeability	10^{-3}	10^{-8}
Soil cover (inches)	60	24
Bottom thickness (feet)	20	15
Average particle diameter (mm.)	0.25	0.002
Organic content of soil	0.5	0
Groundwater BOD	10	10
Cation exchange capacity	0	80
Buffering capacity (meg)	7	4
Groundwater travel distance (miles)	750	750
Gradient (ft/mile)	5	5
Population within 25 mile radius	10^6	10^6
Prevailing wind direction	WNW	WNW

Site #1 ranking parameters - Ip=11.5, Lp=5, Fc=14.5, Ac=5, Oc=1, Bc=7,
Td=5, Gv-1.66, Wp=4.05, and Pf=6

Total landfill rank (Site #1) = 60.71

Site #2 ranking parameters = Ip=1.03, Lp=0.145, Fc=3.2, Ac-0, Oc-1,
Bc=4, Td=5, Gv=0.625, Wp=2.9, and Pf=6

Total landfill rank (Site #2) = 23.9

Landfill #2 having a much smaller rank than landfill #1 would obviously be more condusive to land disposal of hazardous wastes."

REFERENCES

0230. Pavoni, J. L., D. J. Hagerty, and R. E. Lee. State of the art of land disposal of hazardous wastes. Paper presented at the Seventh American Water Resources Conference, Washington, D. C. Oct. 24-28, 1971.

0772. Sorg, T. J. and H. L. Hickman, Jr. Sanitary landfill facts. Washington, U. S. Department of Health, Education, and Welfare, 1970. 30 p.

1509. California State Department of Public Health. Tentative guidelines for hazardous waste land disposal facilities. Jan. 1972. 42 p.

OCEAN DUMPING OF HAZARDOUS WASTE MATERIALS

1. INTRODUCTION

The oceans have always served both man and nature as the ultimate disposal sink for all of the waterborne waste material carried by the natural and man-made streams discharging at their shores, and for all of the atmospheric pollutants scrubbed from the air by the rain that falls on their surfaces. In addition, with increasing frequency in this century, hazardous waste materials have been deliberately shipped out to sea and dumped as either an expedient or an economically attractive disposal technique. The hazardous waste materials thus disposed of have varied widely in type, in quantity, and in frequency of disposal. Three examples of this diversity may be cited as typical:

(1) "Spent" sulfuric acid (7 to 10% H_2SO_4, and up to 30% $FeSO_4$) wastes from steel pickling and titanium oxide pigment manufacture processes are shipped daily to sea in specially designed barges, at the rate of 2.7 million tons per year.[0056]

(2) The U. S. Army program for deep sea disposal of obsolete chemical munitions was terminated in 1970 with the scuttling in the Atlantic of a stripped cargo vessel laden with 418 concrete vaults which contained a total of 135,432 lb of GB chemical warfare agent (non-persistent "nerve gas") and 32,605 lb of explosives.[0353]

(3) Individual 55-gal. drums filled with sodium metal sludge (75% Na, 25% Ca) are pierced and dropped from the decks of merchant vessels into the Gulf of Mexico on an intermittent, unscheduled basis.[0056]

The three examples cited above illustrate the three basic techniques for ocean disposal of hazardous waste materials. The first basic technique is bulk disposal of liquid or slurry-type wastes. The waste materials are loaded into barging equipment--generally, specially designed tank barges. The barges are towed to sea, and emptied while underway at off-shore distances that range from 10 to 125 miles.

In the past, the U.S. Army and U.S. Navy have stripped obsolete or surplus World War II cargo ships, and loaded the ships with obsolete munitions of all types. The "explosive waste" laden bulks were towed out to the pelagic depths beyond the Atlantic and Pacific continental shelves, and scuttled in pre-designated sites.

The third basic technique employed for deep sea disposal of hazardous materials is the sinking at sea of containerized hazardous/toxic wastes. The individual containers, generally 55-gal. drums, are carried as deck cargo on merchant vessels, and are discharged overboard at distances from shore that, dependent upon the contents, may be well over 300 miles.

2. OPERATING PRINCIPLE

The operating principles involved in the three basic techniques employed for deep sea disposal differ in their use of the ocean. Sea water is used as a reacting, neutralizing medium and/or a diluent in the bulk disposal of industrial wastes from tank barges. By contrast, obsolete munitions detonated in the deep sea employ the ocean as a cushioning, isolating medium, to protect the "on-shore" environment from the effects of the detonation. Similarly, disposal of concrete-encased obsolete chemical munitions and (undetonated) obsolete conventional ordnance items by "burial" in several thousand feet of water use the ocean as a means of isolation, to minimize or prevent both potential and actual impact upon the on-shore ecosphere.

The deep-sea disposal of containerized hazardous wastes is based upon the principles cited above. Where the drums are deliberately ruptured at the surface, the ocean is used as reactant and/or a diluent. Those drums that are weighted and sunk intact beyond the continental shelf employ the thousands of feet of water for protective isolation of the barrels and their contents.

The District Offices of the U.S. Army Corps of Engineers have handled all applications for permission to engage in ocean disposal of hazardous (and other) waste materials. If the other Federal (and State) agencies to whom the Corps circulates the application are "reasonably agreeable," the Corps issues a "letter of no objection" to the applicant tantamount to an authorization to proceed.[0056] The Corps may, in addition, specify

TABLE 1.[0056]

MARINE DISPOSAL AREAS FOR HAZARDOUS WASTES
(BY REGION AND WASTE TYPE)

Waste Type	Pacific	Atlantic	Gulf	Total
Industrial waste	9*	15*	16	40
Radioactive waste	10*	25*	2	37
Explosive and chemical munitions	19*	19*	11	49
Total	38	59	29	126
(No duplicates)				

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*Areas used for two or more types of wastes.

2. Irreversibility of the impact of dumping.

3. Volume and concentration of materials involved.

4. Location of disposal, i.e., depth and potential impact of one location relative to others."[0374]

(7) Give high priority to protecting the estuaries and shallow, near shore areas. Specifically, the Council made the following recommendations to discontinue, prohibit, or phase out the ocean dumping of the various categories of hazardous wastes:

1. Continue prohibiting the ocean disposal of high-level radioactive wastes.

2. Prohibit the ocean disposal of all other radioactive wastes, excepting only the federally regulated discharge from vessels and land-based nuclear facilities of low-level liquid wastes, or such other low-level radioactive wastes as have no alternative offering less harm to man and the environment.

3. Prohibit further ocean disposal of chemical warfare materials.

4. Continue prohibiting the ocean disposal of biological warfare materials.

5. Terminate as soon as possible ocean dumping of explosive munitions.

6. Terminate immediately dumping of toxic industrial wastes, excepting only those which have no alternative offering less harm to man and the environment.

7. Phase out ocean dumping of all industrial wastes.

A number of studies have been made of the environmental effects of ocean dumping of hazardous materials. Due to the (unique) requirement by the Galveston District of the Corps of Engineers, that laboratory and field studies of the effects of the wastes be filed in support of disposal applications, the majority of these studies have been carried out in the Gulf of Mexico.[0056] Inspection of the results of the various studies performed (see Table 2 for a summary of the key findings) indicates that the toxic effects of the hazardous chemical and pesticide wastes are generally limited to short time periods and areas in immediate proximity to the discharge or regulatory procedures to be followed in connection with the disposal processes.

There were 281 ocean areas designated for the disposal of wastes of all types in 1969. Of these areas, 117 were employed for the disposal of hazardous wastes. The regional distribution of these locations is summarized by Smith and Brown (Table 1).[0056]

The report to the President on ocean dumping by the Council on Environmental Quality[0374] makes a number of strong, broad-based recommendations "to ban unregulated ocean dumping of all materials, and strictly limit ocean disposal of any materials harmful to the marine environment." Specifically, legislation is recommended to:

(1) Require a permit from the Administrator of the Environmental Protection Agency (EPA) for ocean, estuary, or Great Lake disposal of any waste.

(2) Authorize the EPA Administrator to ban specific materials and specify safe sites.

(3) Provide for Coast Guard enforcement, and establish penalties for violations.

The Council recommended the use of the following principles in regulating ocean disposal:

(4) Stop ocean dumping materials clearly identified as harmful to the marine environment or man.

(5) Phase out ocean disposal where existing information on effects is inconclusive but where "best indicators" are that the materials dumped could create adverse conditions. If and when conclusive proof is obtained that disposal of the materials in question produces no damage to the environment (short term, cumulative, and long-term), permit dumping under regulation.

(6) Include in the criteria for setting disposal standards and for urgency in stopping disposal operations:

    1. "Present and future impact on the marine environment, human health, welfare and amenities.

TABLE 2.

SUMMARY OF ENVIRONMENTAL STUDIES ON INDUSTRIAL WASTES DISCHARGED AT SEA[0056]

Waste Type	Disposal Area		Barging Characteristics				Waste Characteristics	Field Observations	Mixing Characteristics		
Industrial	Distance from shore (miles)	Water depth (feet)	Amount of waste/ trip	Depth of discharge	Rates of discharge tons/min	Towing speed (knots)	Given description	Observed effects	Initial dilution	Diffusion coefficient cm^2/sec.	General study conclusions
Spent sulphuric acid	15 from New Jersey coast	80	3200 tons 5000 tons	15 feet	18 70	6 7	Fe_2SO_4 (10%) H_2SO_4 (8.5%)	Water discoloration plankton temporarily immobile iron settled rapidly from surface layer, no appreciable accumulation of iron found in bottom sediments.	1:5,000	2.9 x 10^3	Mixing and diffusion of wastes occurs rapidly in the wake of the barge. No evidence to indicate adverse effects
Chlorinated hydrocarbons	125 SE of Galveston, Texas	2400	1200 tons	12 feet	5	6	Beta-chloropropylene (22%), trichloropropane (5%) isopropylchloride (38%) allylchloride (11%) misc. chlorides (33%), heavy ends (3%) pH 9.8 specific gravity 0.9 1.34	Water discoloration fish plankton killed on direct contact of waste no harmful effects seen after 2.4 hrs. Bulk of waste sank. Low diffusion of waste at depth		2.5 x 10^3 (average)	Disposal of toxic wastes at sea can be accomplished with only a slight effect on organisms in the biomass within a limited oceanic area
Paper mill wastes (black liquor)	125 SE of Galveston, Texas	2400	1300 tons	10 feet	5	6	Paper mill wastes 47% solids. BOD, 100,000 ppm Na_2CO_3, Na_2SO_4, NaOH etc., pH 13 Specific gravity 1.27 at 60°C	Slight water discoloration. No mortality to marine life. Bulk of waste sank	1:300,000	2.5 x 10^3 (average)	Disposal of "black liquor wastes" in the deep sea can be accomplished without determinable effects on marine biota. Ultimate disposal is expected to be accomplished by bacteria. Advisable to monitor each separate load of waste to determine toxicity in laboratory
Ammoniasulphate (mother liquor)	100 S of Freeport Texas	2760	1700 tons		7	4	Ammonium sulfate (23%), nitrogen (8%), carbon (12%), organics (29%) (alcohols, esters amides) IOD 90 MG/L BOD, 57,000 ppm, pH 4.3, S.G. 1.23	No fish mortality. No floating oil. Bulk of waste sank. Maximum waste concentration at depth		9 x 10^2	No undesirable effects were observed. Diffusion great enough to ensure good dispersion to minimize harmful effects to biota.
Waste liquor	70 S of Freeport Texas	960	2400 tons		5-24	6	Na_2S (Na_2S_2) (6%) (Na_2S_3) NaHS 1% S (total) (6%), NaCl (21%), organic 2%, solids (dissolved and suspended), specific gravity 1.24 at 60°C.	No evidence of subsurface maximum waste concentration.	1:10,000- 1:100,000 in 2 hrs		Disposal should produce no significant mortality in the biota, nor any prolonged effects.
Chlorinated waste liquor	125 SE of Galveston, Texas	2400	1400 tons (proposed)		13-25 (recommended)	5 (recommended)	(Organic waste) chlorinated organics (10-15%), inorganic salts (Na_2SO_4) (5-6%), (acid) chlorinated organics (1%) sulfuric acid (10-15%), nitric acid (0.1%)				No significant mortality would be expected from disposal of this waste in the open ocean
Sodium sludge (contaminated)	110 S of Galveston, Texas	2400	15 55-gal drums (500-570 pounds per drum)	Surface	Variable	10	Metallic sodium (75%) calcium (24%) barium, magnesium potassium (1%)	No mortality to fish. Flying debris hazardous to disposal personnel. 30% mortality to plankton due to collection methods			Explosions caused by reaction of sodium with seawater had no significant effects on *sargassum* and zooplankton populations. Absence of fish kiln was probably due to barrenness or disposal area.
Pesticides	95 SSE of Galveston, Texas	720	50 55-gal drums per trip	1200 ft	1 barrel/2 mins (600 intervals on bottom)	3	Anilines (chloroaniline monochlorobenzene), liquid organics (methanol, p-xylene chlorobenzene), dry chemicals—insoluble (*thiram thiram-E, thionex, zineb ferbam, monuron*, carbon disulfide)		100:1	0.002 x 10^3	Consideration of available toxicity and diffusion data from literature sources indicate that the zone of water containing toxic concentrations of waste surrounding each disposal drum will be limited in extent and duration and will not endanger motile aquatic life in the disposal area to a significant degree

dump.[0056] The rate of dilution is, in general, so high that, after 12 hours, it is impossible to detect analytically chemical differences between "contaminated" and uncontaminated sea areas. The toxic effects of waste acid discharged from tank barges at sea are minimal;[0056] the zooplankton from samples in the immediate discharge zone were immobilized temporarily, but recovered rapidly in unpolluted water. Chlorinated hydrocarbon wastes discharged in Gulf waters killed fish and plankton in direct contact with the undiluted waste.[0056] In contrast, due to dilution, there was no effect observed on marine life at the surface two to four hours after discharge. The general ocean surface and upper level effects of chlorinated hydrocarbon discharge range downward from the upper extreme noted above - fish and plankton kill - through laboratory-study-detected inhibition of photosynthesis and respiration[1783] to total absence of observable effect. The possible effects of the discharged chlorinated hydrocarbons at deeper levels, and on the bottom, have not been determined.

Smith and Brown[0056] report that unpierced barrels loaded with sodium sludge (75 percent metallic sodium, 24 percent metallic calcium) have on two occasions been retrieved in the Gulf of Mexico by fishermen. These barrels were not pierced prior to dumping as prescribed, nor were they dumped in the prescribed area. Pierced barrels of the sodium sludge exploded when dropped overboard, produced no significant effects on the nicrobiota, and, due to the probable barrenness of the area, produced no visible fish kill.

The probable effects of deep-sea disposal in the Gulf of Mexico of weighted steel drums, designed to rupture on the sea floor, and containing herbicide and fungicide wastes (chloraniline, aniline, monochlorbenzene, methanol, p-xylene, theram, theram-E, Thionex, Zmeb, Ferbam, and carbon disulfide) were studied on a theoretical basis.[0056] No field (at-sea) confirmation of the study findings - that dilution due to eddy diffusion and chemical degradation would reduce concentrations to below the median tolerance limits[0056]--have been reported. On the contrary, pesticides at sublethal dosages have been shown to reduce the size and strength of mollusk shells, and to reduce growth rate and reproduction activity in fish.[0374]

The National Academy of Sciences - National Research Council (NAS-NRC) Committee of Oceanography, on the basis that the understanding of most of the physical and biological processes in the ocean was too poor "to permit precise predictions of the results of the introduction of a given quantity of radioactive materials at a particular location in the sea,"[0056] proposed attacks upon several basic problem areas. These were all oriented towards the potential hazards associated with deep sea disposal of radioactive wastes. The most critical of these is the possibility of return of the radioactivity to humans. Second in criticality was marine organism damage due to exposure to radioactive waste. The two avenues cited[0056] for occurrence of such damage are (1) transport of the radioactive wastes from the disposal sites to the coastal zone, and (2) uptake of the radioactive wastes by one or more of the trophic levels in the marine biota, with possible return to man via commercially important fish and shellfish.

The NAS-NRC studies produced reports[2612,2613,2614] which covered the key factors to be considered in disposal of low level radioactive wastes at sea--both containerized, and liquid wastes from vessels and outfalls--and the disposal sites selections. Relatively little of the further research recommended in the NAS-NRC reports to fill in the wide gaps in factual data has been carried out. As of 1969[0056] only three off-shore sites employed for disposal of low-level containerized radioactive wastes had been resurveyed for the Atomic Energy Commission.[0056]

(1) The site near the Farallon Islands, off San Francisco.

(2) The Santa Cruz basin site, west of Los Angeles (70 miles)

(3) The site 130 miles east-southeast of Cape May, New Jersey.

The first two sites, based on beta-gamma counting of sediment samples, had no apparent radioactive waste leakage. There were some indications in 1961, based on similar counts, of possible leakage from the containers at the site off Cape May. There are no reports of further investigations. As noted earlier, low-level radioactivity liquids discharged from vessels and nuclear facilities, if as per federal regulations and international standards, have not been recommended for termination; the ocean dumping of other radioactive wastes was.[0374]

The President's Council on Environmental Quality, in the report on ocean-dumping[0374] cited earlier, recommended termination of the disposal of chemical warfare materiel and explosive munitions by dumping at sea. As support for this recommendation, a Department of Defense calculation was cited which indicated that the 1,000 tons of explosives detonated in Deep Water Dump in the Pacific off Washington on September 4, 1970 was capable of generating a shock wave that would "kill most marine animals within 1 mile of the explosion and will probably kill those fish with swim bladders out to 4 miles from the explosion."[0374] It should be noted that, of 15 explosive ordnance laden bulks scuttled, 12 detonated during scuttling.[0471]

President Nixon, in response to the above recommendation and the others cited earlier, stated on October 7, 1970 that he would recommend legislation to stop ocean dumping. The Secretary of the Navy immediately placed a moratorium on Deep Water Disposal (DWD) operations.[0471] Subsequently, the Chief of Naval Operations directed that an investigative program for conventional explosives, be instituted to prepare a comprehensive environmental condition report on representative past explosive ordnance DWD Sites; develop criteria for selection of future DWD sites; and determine the monitoring required at future DWD sites.[0471] This program was started in the late spring of 1971. The representative sites selected were: an area off Cape Flattery in the Pacific, where five ships were sunk and exploded in 8,400 ft of water and an area 175 miles southeast of Charleston where one ship was sunk and did not explode, in 6,300 ft of water.[0471] The program will be completed early in 1972. Results to date show no evidence of cratering of the sea floor in the Pacific. "A substantial number of organisms typical to the general region are apparently residing within the debris area."[0471]

There has been some fear that the ocean disposal of chemical warfare munitions by techniques similar to those used in CHASE involved the possibility that the explosive portions of the munitions would detonate after sinking, and release the chemical warfare agent.[0056] In this context, the chemical warfare material encased in concrete vaults that were disposed of in 7,000 ft of water by scuttling the laden bulks off New Jersey in 1967 and 1968 did not explode and rupture the vaults.[0353] It was also stated that sea water, because of its alkalinity, will both hydrolyze and dilute any chemical warfare agent that is released.[0353]

3. OPERATING DESIGN

Deep sea disposal bulk transport systems vary from modern, specialized tank barges to obsolete hulks.[0482] The majority of bulk liquid and slurry hazardous wastes dumped at sea are transported in specially designed tank barges, from 1000 to 5000 short tons in capacity. The tank barges are of double-skinned bottom construction, and must be certified for ocean waters by the U.S. Coast Guard. The barge cargo is under U.S. Coast Guard regulations covering the bulk shipment of chemicals from the U.S.

Industrial waste-laden barges are transported to the industrial waste disposal areas designated in Figures 1, 2, and 3 for the Pacific, Atlantic, and Gulf of Mexico coasts, at off-shore distances that depend upon the type of waste and the regulatory procedures. Typical distances are, for acid wastes, 15 miles from New York City; for toxic chemical wastes, 125 miles into the Atlantic; for Gulf of Mexico operations, 125 miles from the coast (at the 2,400 ft depth line). In the disposal area, typical barge speeds from 3 to 6 knots are used; typical discharge is at 6 to 15 ft submergence, at rates that vary between 4 and 20 tons per minute.[0056] A characteristic prediction rate for chlorinated hydrocarbon concentration in the disposal area is $C = \frac{\text{pumping rate}}{0.063t}$ where C is concentration in parts per million (p.p.m.); pumping rate is in grams per centimeter and t is time in minutes after pumping.[1783]

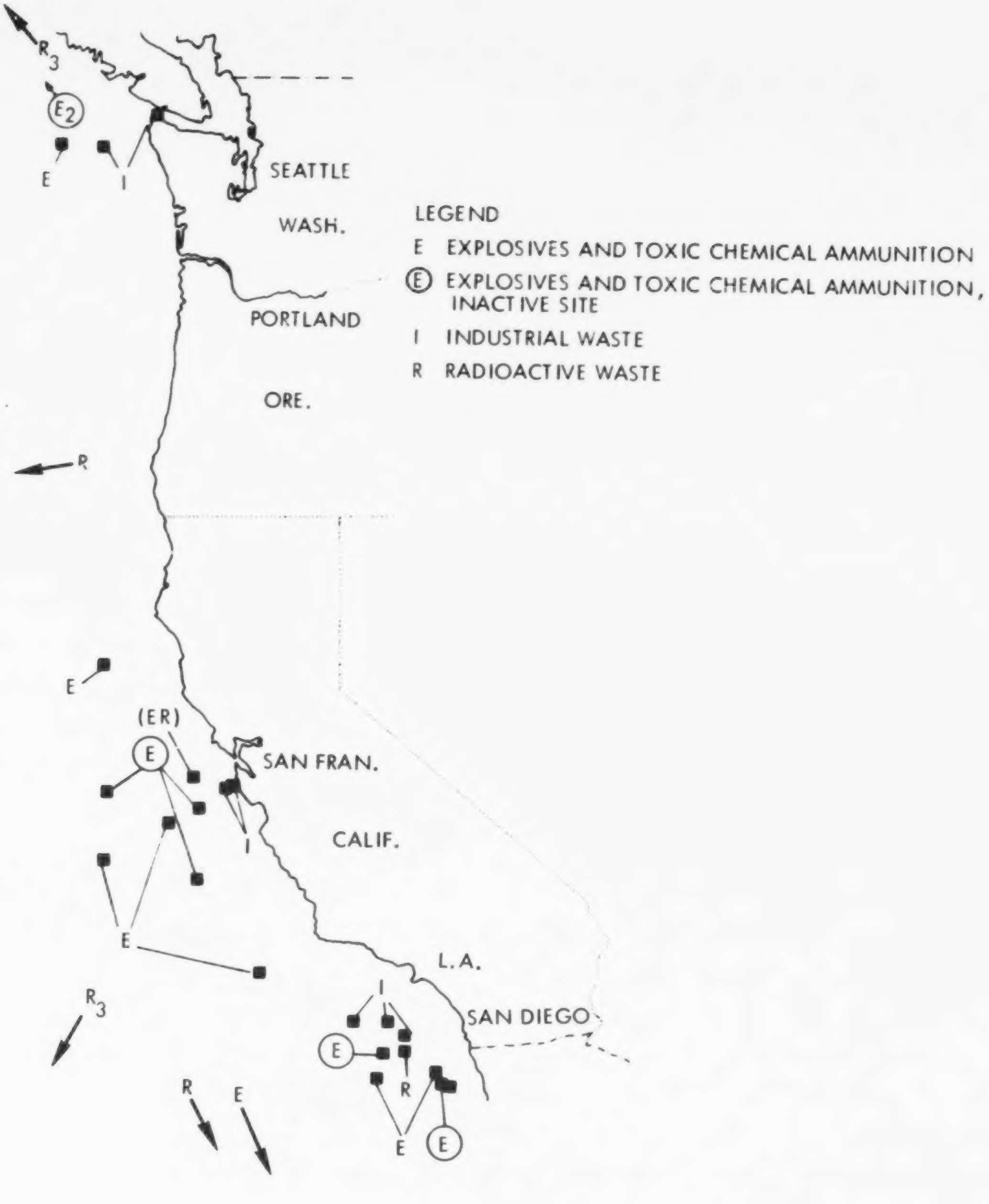
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Figure 1. Pacific Coast Disposal Areas[0056]

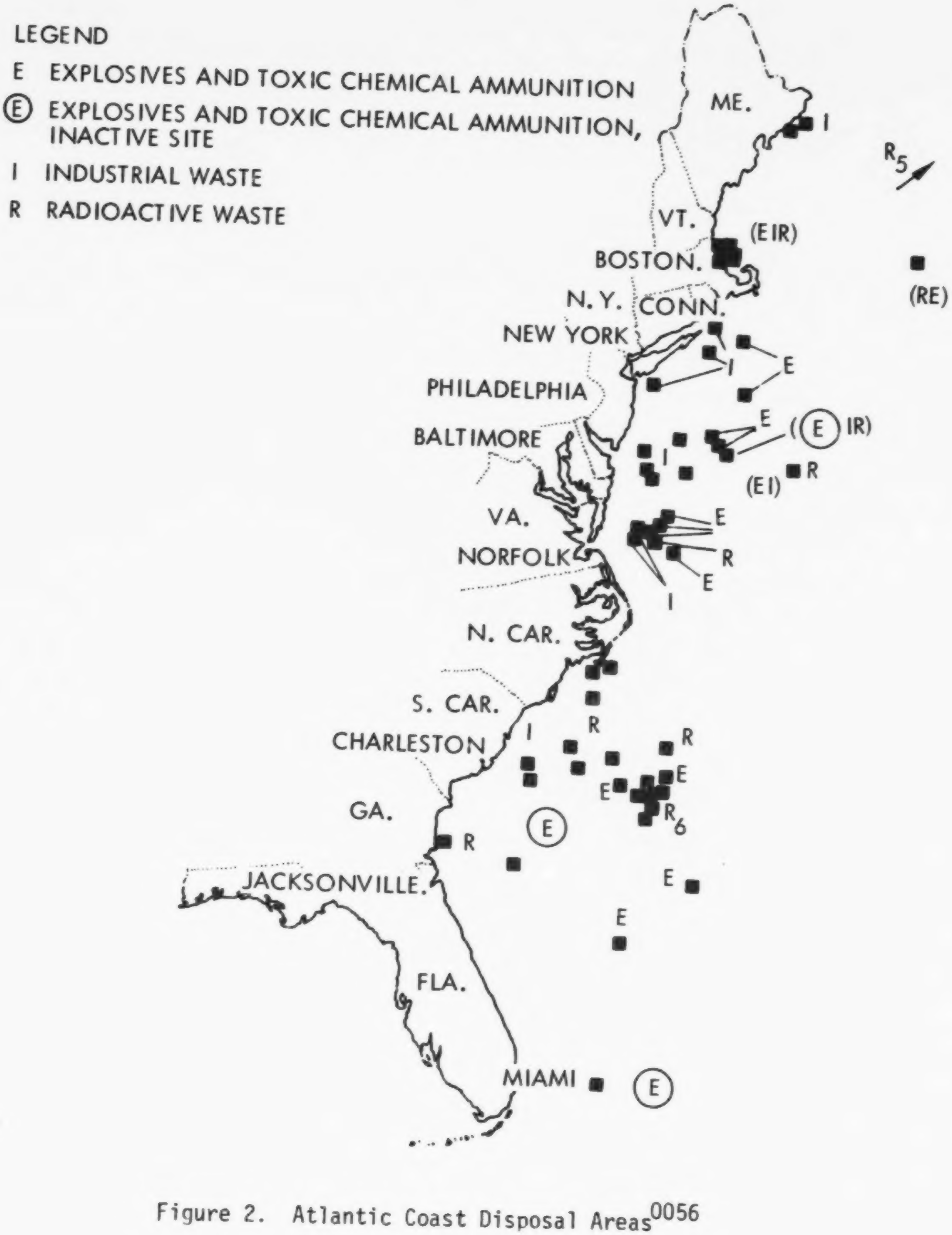
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Figure 2. Atlantic Coast Disposal Areas[0056]

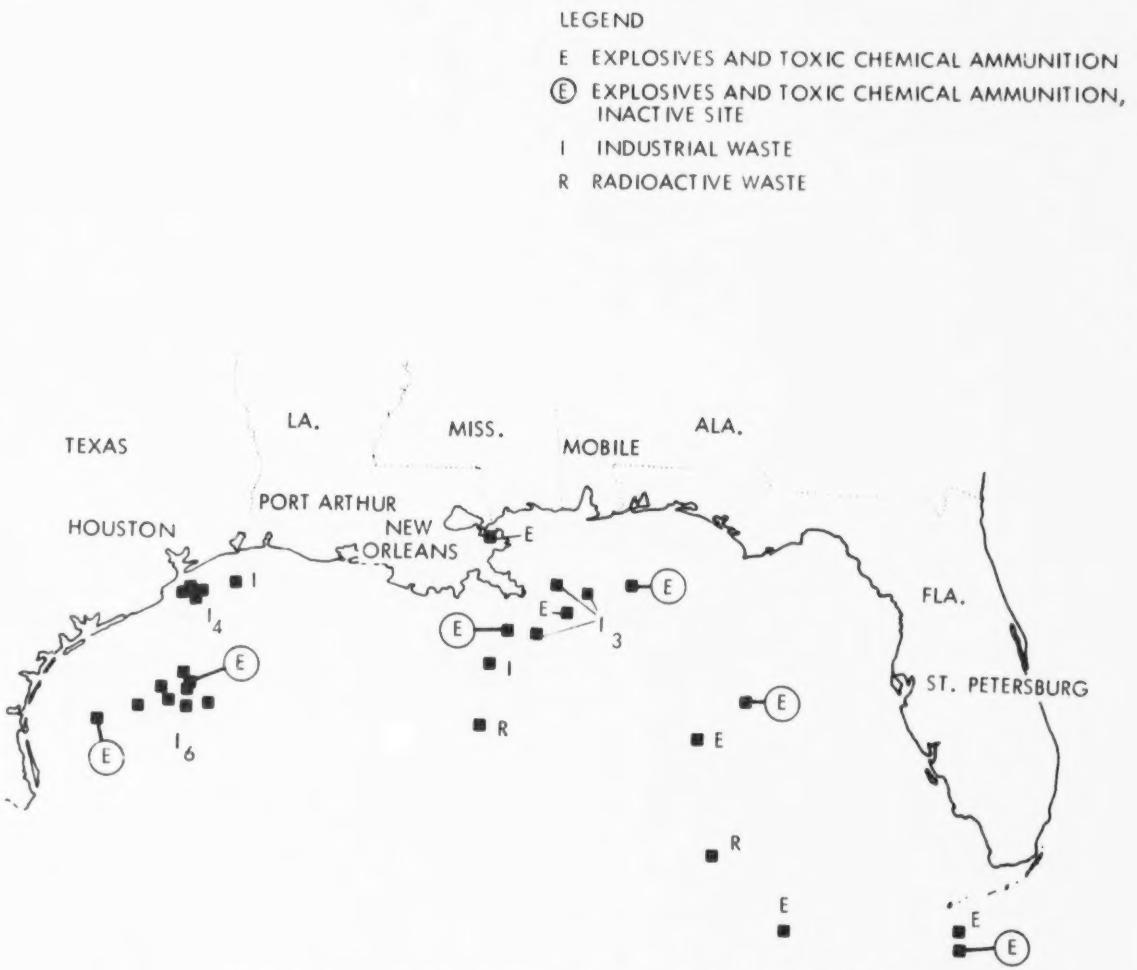
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Figure 3. Gulf of Mexico Disposal Areas[0056]

The last practice employed in deep water disposal of obsolete explosive and chemical warfare ordnance was that of the U.S. Navy CHASE (Cut Holes And Sink 'Em) disposal program. The Navy, which handled deep water dumping of munitions for all of the services, obtained merchant hulks for this purpose from the U.S. Maritime Administration Reserve of surplus World War II merchantmen. The ship was stripped of anything readily removable or loose. The fuel tanks were cleaned to eliminate oil contamination and scuttling valves were installed to allow water to enter the ship. To permit the water to spread evenly, soft patches were installed in the bulkheads between the holds. The material for dumping was made negatively buoyant (bulk density higher than sea water), to prevent it from floating to the surface, and loaded into the bulk at one of two Naval Depots (Earle, New Jersey, or the former Naval Ammunition Depot at Bangor, Washington.[0056]

After the operation had been cleared with all responsible authorities, the munition-laden hulk was towed to the selected dumping site under naval escort, and scuttled. The selected sites have been at least 10 miles from any shore, and in waters at least 3,000 ft deep. The majority of sites employed before the moratorium on DWD were at sea depths in excess of 6,000 ft.[0056] Of the 15 explosive laden hulks scuttled, four were detonated deliberately (two at 1,000 ft depth, two at 4,000 ft depth)[0374] and eight detonated unintentionally.[0471]

Low level radioactive wastes have in the past been encased in concrete contained in 55-gal.-steel drums, which were required by AEC regulations to be of a minimum gross weight of 550 lb, to ensure sinking. Another packaging technique has been to encase 55-gal.-drums, loaded with liquid low level radioactive wastes, in a concrete block. The concrete packages wastes were then taken to designated disposal sites, and dropped overboard. Most of the wastes disposed of in the Pacific were dumped at two sites. Disposal in the Atlantic, with one exception, has been at depths greater than 6,000 ft. The exception (in the area of Massachusetts Bay, about 12 to 15 miles offshore) was in 300 ft of water.[0374]

Low level radioactive liquid wastes, resulting from the operation of U.S. Navy nuclear submarines, are discharged at sea in accordance with regulations on depth and rate of pumping. As of 1970, one commercial organization, two government agencies, and one university were the only entities authorized to dispose of radioactive wastes in the ocean.

Containerized toxic industrial wastes, as noted earlier, are dumped at sea after transport as deck cargo on either merchant vessels or contract disposal vessels. The individual containers are either ruptured at the surface, or weighted for sinking. These is no single "operating design" or operating practice that covers the wide variety of materials thus disposed of.

4. ECONOMICS

The average cost for ocean disposal of all types of wastes in 1968 (Table 3) was slightly over \$0.60 per ton.[0056] The 1968 average cost for disposal of bulk industrial wastes was \$1.70 per ton. Average ocean disposal costs for explosives in 1968 were \$15 per ton. Since the quantity of containerized low-level radioactive wastes dumped at sea in 1968 was zero, and only 4.2 tons per year were dumped in 1969 and 1970, costs were not calculated for this category. The ocean disposal costs cited for industrial wastes and miscellaneous wastes represent transportation and dumping costs only, and do not include other costs incurred for treatment, storage and loading of the wastes. The costs reported for explosives include hull preparation, towing and loading costs, and are given as dollars per ton of total waste cargo.

The costs for ocean dumping of industrial wastes are significantly lower than those of other disposal techniques currently employed. The costs of minimum environmental impact disposal techniques for the bulk industrial wastes are very much higher than the costs of ocean dumping. As an example, material (lime) costs for neutralization of the waste acid from TiO_2 pigment manufacture are estimated at roughly \$1.00 per ton; operating costs and

TABLE 3.

1968 COSTS PER TON FOR MARINE DISPOSAL OF HAZARDOUS WASTES IN THE UNITED STATES COASTAL WATERS[0056]

Type of Waste	Total United States		Pacific Coast		Atlantic Coast		Gulf Coast	
	Average Cost	Reported Range	Average Cost	Reported Range	Average Cost	Reported Range	Average Cost	Reported Range
Industrial Wastes								
Bulk	$1.70/ton	$0.60-9.50/ton	$1.00/ton	$0.60-9.50/ton	$1.80/ton	$0.60-7.00/ton	$2.30/ton	$0.75-3.50/ton
Containerized	$24/ton	$5-130/ton	$53/ton	$50-130/ton	$7.73/ton	$5-17/ton	$28/ton	$10-40/ton
Explosives	$15/ton	$15-90/ton	-	-	-	-	-	-
Miscellaneous*	$15/ton	$5-600/ton	$15/ton	$5-600/ton	-	-	-	-

Note: Although Reference 0056 quotes costs as "on the basis of the weight of the volume of water in which the wastes were contained", marine costs are generally quoted on the basis of the weight of the volume of water displaced. It is believed that the costs cited in this table are so based.

*Includes barreled chemicals and sludges equipment amortization would add at least an equal amount, and land burial with its attendant costs would still be required for the solid calcium sulfate-iron hydrate produced as a product of neutralization, after recovery by lagooning or filtration.

In general, the predominant factors which have given rise to ocean disposal of hazardous wastes have been economic - avoidance of capital outlay, and/or a cheaper operating cost than the costs of other techniques. This economic incentive will be increased as federal and local regulations increase the requirements for the use of minimum impact disposal techniques, with their attendant higher costs. Few of the hazardous waste materials currently disposed of by ocean dumping present an economically attractive recycle or by-product recovery picture. Recycling and reprocessing of "waste acid" (generally, waste sulfuric acid) which constituted 58 percent of the bulk industrial wastes dumped at sea, has been the objective of many economically fruitless steel and pigment company research and development projects. In fact, the major reason for the changeover from sulfuric acid to hydrochloric acid as the preferred material for pickling of steel was the virtual impossibility of economic recycle via regeneration of the spent sulfuric acid.

5. PROCESS APPLICATIONS

The list of hazardous waste materials dumped in the ocean is almost endless. The broad classes of hazardous waste materials have been categorized as follows:[0056] Industrial wastes; obsolete, surplus, and nonserviceable conventional explosive ordnance and chemical warfare material; radioactive wastes; miscellaneous hazardous wastes. The major types of industrial waste dumped at sea which are considered hazardous are: Spent acids; refinery wastes; pesticide wastes; and "chemical wastes." Other, lower hazard industrial waste types disposed of at sea are: Pulp and paper mill wastes; oil drilling wastes; and waste oil. Conventional explosive ordnance and chemical warfare material which has received deep water disposal includes nonserviceable or obsolete shells, mines, solid rocket fuels, propellants, small arms ammunition, rockets, pyrotechnics, and mines and rockets containing HS, GB and VX lethal chemical warfare agents. The "miscellaneous waste" category covers, for the most part, materials disposed of in small lots, without sanction by any regulatory authority. Hazardous wastes covered under this catch-all heading include pesticides and complex chemical solutions.

There were 4.7 million tons of all types (hazardous and non-hazardous, bulk and containerized) of industrial waste dumped at sea in 1968 (Table 4). Conventional and chemical warfare munitions subjected to ocean disposal in 1968 totaled 15,200 tons. No containerized radioactive materials were ocean dumped in 1968 (average for 1969-1970 was 4.2 tons per year). "Miscelaneous" wastes amounted in 1968 to an estimated 200 tons.[0056]

The hazardous industrial wastes which consitiute by far the largest class of hazardous waste materials dumped at sea are waste products of pigment processing, steel production, petroleum refining, petrochemicals manufacture, insecticide-herbicide-fungicide manufacture, chemical manufacture, and metal finishing-cleaning-plating processes, amongst many others. Some of the specific hazardous industrial wastes dumped at sea are:

Spent Acids

Sulfuric acid is used in large quantities by the steel mills to pickle (remove surface rust and mill scale from) steel stock (rod, bar, sheet, plate, and the like) prior to fabrication or other manufacturing processes. The acid ("pickle liquor") is usually removed from further process use when between one-half and two-thirds of the free acid has been converted to ferrous sulfate by reaction with the steel and iron oxides. The spent acid sent to disposal contains up to 7 percent free H_2SO_4 and up to 30 percent $FeSO_4$.

In some steel plants, hydrochloric acid is used for all or part of the pickling, and the spent acid wastes contain free hydrochloric acid and ferrous chloride instead of, or in addition to, the sulfuric acid and ferrous sulfate resulting from the use of sulfuric acid for pickling.

TABLE 4.

SUMMARY OF QUANTITIES OF HAZARDOUS WASTES DISPOSED OF IN UNITED STATES COAST WATERS - 1968[0056]

Waste Type	Pacific Coast Annual Tonnage	Atlantic Coast Annual Tonnage	Gulf Coast Annual Tonnage	Total Annual Tonnage
Industrial Wastes	981,300	3,013,200	696,000	4,690,500
Bulk	981,000	3,011,000	690,000	4,682,000
Containerized	300	2,200	6,000	8,500
Munitions	--	15,200	--	15,200
Radioactive Wastes	--	--	--	--
Miscellaneous*	200	--	--	200
Total, All "Hazardous" Wastes†	981,500	3,028,400	696,000	4,705,900

*Rough Estimate

†Includes all categories of industrial wastes dumped at sea

Sulfuric acid is also used in large quantities by titanium pigment plants, which digest the ore (whose principle impurity is iron) with H_2SO_4. The process wastes are in the form of a liquor which contains 7 to 9 percent free H_2SO_4, 8 to 10 percent $FeSO_4$, and a mud slurry with 15 to 20 percent inert solids.

Spent acid wastes dumped at sea comprise 58 percent of all industrial wastes so disposed of, or about 2,700,000 tons.[0056]

Refinery Wastes

Petroleum processing operations produced about 12 percent (about 560,000 tons)[0056] of the total industrial wastes dumped in the ocean in 1968. Refinery wastes include spent caustic soda solutions, sulfuric acid sludges, dilute process water solutions, spent catalysts, waste petrochemicals, and chemical cleaning wastes. The solid wastes (spent catalysts and sludges) are frequently slurried with the liquid wastes prior to shipment to sea for disposal. Varying amounts of sulfides, phenolates, napthenates, cyanides, heavy metals, mercaptides and chlorinated or brominated hydrocarbons are among the hazardous minor contaminants of the refinery wastes.

Chemical Wastes

A wide variety of waste chemicals dumped at sea is produced by chemical manufacturing, chemical laboratory, metal cleaning-finishing-electroplating, and other industrial operations. These include mercury and arsenic compounds, chlorinated hydrocarbons, alkalies, anilines, cyanides and other highly toxic substances. There is no valid estimate of the tonnage of these wastes for 1968.

Pesticide Wastes

Pesticide (insecticide, herbicide, and fungicide) manufacturing operations produced about 7 percent (290,000 tons) of the total industrial wastes disposed of at sea in 1968. Of this amount, about 170,000 tons were barged down the Mississippi from the Memphis/upriver area and dumped 100 miles offshore from Beaumont, Texas into 1,200 ft of water.

6. RECOMMENDATIONS

It is believed that the recommendations of the President's Council on Environmental Quality should be reconsidered in the following specific areas after the prerequisite research has been performed:

(1) Termination of the ocean dumping of explosive munitions

(2) Phase-out of ocean dumping of spent sulfuric and/or hydrochloric acid wastes from steel pickling, and from titanium pigment manufacture

On the basis of data presented by Captain Reed,[0471] the dumping in the ocean of conventional explosive munition at selected, pre-designated charted sites where depths are in excess of 6,000 ft presents no apparent hazard if the munitions are not detonated, and a minimal impact where the munitions detonate at the lower depths. Similarly, the evidence presented by Smith and Brown[0056] if verified by additional laboratory and field test findings in the Atlantic, indicates a minimal acceptable impact on the ecosphere if proper current practice is followed for acid unloading at prescribed depths and rates while underway at usual tow speeds in designated deep sea disposal areas. Further research with these specific wastes and with other selected materials is necessary to determine the necessary additional information on the effects of the selected materials on the ocean environment. Additionally, the effects of the ocean environment on the wastes to be dumped must also be determined to ensure that toxic materials are not formed as the result of reaction and interaction. Finally, research is necessary to develop waste forms stabilized to ensure compatibility with the ocean environment on both short and long term bases.

7. REFERENCES

0055. Gunnerson, C. G., D. D. Smith, and R. P. Brown. An appraisal of marine disposal of solid wastes off the west coast: a preliminary review and results of a survey. 15th Annual Meeting, Institute of Environmental Sciences, Anaheim, California, Apr. 23, 1969.

0056. Smith, D. D., and R. P. Brown. Ocean disposal of barge-delivered liquid and solid wastes from U. S. coastal cities. (Dillingham Corporation, La Jolla, California). Contract No. PH 86-68-203, U. S. Environmental Protection Agency, Solid Waste Management Office, 1971.

0057. Smith D. D., and R. P. Brown. Deep sea disposal of liquid and solid wastes. Industrial Water Engineering, Environmental Protection Agency, Sept. 1970.

0353. Ocean disposal of unserviceable chemical munitions. Hearings, Subcommittee on Oceanography, Committee on Merchant Marine and Fisheries, House of Representatives, 91st Congress, Aug. 1970. Serial No. 91-31.

0374. Ocean dumping; a national policy. Council on Environmental Quality, Report to the President, Oct. 1970. 45 p.

0471. Reed, Jr., W. F., Captain, U.S.N. Assessment of the environmental effects of past deep water dumping operations. Thirteenth Annual Explosives Safety Seminar, Minutes, Armed Forces Explosives Safety Board, San Diego, California, Sept. 1971. 257 p.

0582. Witt, Jr., P. A. Disposal of solid wastes. Chemical Engineering, 78(22):62-78, Oct. 4, 1971.

0857. Dumping of waste material. Hearings, Subcommittee on Fisheries and Wildlife Conservation, Committee on Merchant Marine and Fisheries, House of Representatives, 91st Congress, July 27, 28, Sept. 30, 1970. Serial No. 91-39.

1783. Hood, D. W., B. Stevenson, and L. M. Jeffrey. Deep sea disposal of industrial wastes. Industrial and Engineering Chemistry, 50(6): 885-888, June 1958.

2612. National Research Council Committee on Oceanography. Radioactive waste disposal into Atlantic and Gulf coastal waters; a report from a working group of the Committee on Oceanography of the National Academy of Sciences - National Research Council. National Research Council Publichation No. 655, Washington, National Academy of Sciences, 1959.

REFERENCES (CONTINUED)

2613. National Academy of Sciences Committee on Effects of Atomic Radiation on Oceanography and Fisheries. Considerations of the disposal of radioactive wastes from nuclear-powered ships into the marine environment. National Research Council Publication 568, Washington, National Academy of Sciences-National Research Council, 1959. 52 p.

2614. National Research Council Committee on Oceanography. Disposal of low-level radioactive waste into Pacific coastal waters. National Research Council Publication 985, Washington, National Academy of Sciences - National Research Council, 1962. 87 p.

INCINERATION

1. INTRODUCTION

The purpose of this process evaluation is to discuss the various types of incineration processes and their applicability to the disposal of waste materials. The report format will be to initially discuss the variables effecting waste combustion such as waste combustibility and combustion temperature, time, and turbulence. A discussion of the variables affecting proper incineration selection such as waste toxicity, disposal rates, corrosiveness, secondary abatement requirements, steam plume generation and waste form will then follow. The remainder of the report will present the particulars on the individual processing units.

Incineration is a controlled process that uses combustion to convert a waste to a less bulky, less toxic, or less noxious material. The principal products of incineration from a volume standpoint are carbon dioxide, water and ash while the products of primary concern,due to their environmental effects are compounds containing sulfur, nitrogen and halogens. When the combustion products from an incineration process contain undesirable compounds, a secondary treatment such as afterburning, scrubbing or filtration is required to lower concentrations to acceptable levels prior to atmospheric release. The solid and liquid effluents from the secondary treatment processes will occasionally require treatment prior to ultimate disposal.

Variables Effecting Proper Waste Combustion

Incinerators are generally classified by the form of waste that they burn--gas, liquid or solid. However, most incinerator systems, regardless of waste type, contain four basic components; namely, a waste storage facility, a burner and combustion chamber, an effluent purification device when warranted, and a vent or stack. It is the oxidation which occurs in the combustion chamber of the system which is of primary importance for proper hazardous waste disposal. It is here that the feed waste is converted to a less hazardous compound and that secondary pollutants which must be removed by further treatment are formed. The variables which have the greatest effect on the completion of the oxidation of the wastes are waste combustibility, dwell time in the combustor, flame temperature, and the turbulence present in the reaction zone of the incinerator.[0304]

Waste Combustibility. Combustibility is a measure of the ease at which a material can be oxidized in a combustion environment. A materials combustibility is characterized by its upper and lower flammability limits, its flash point, ignition temperature and autoignition temperature. In general materials with a low flammability limit, low flash point, and low ignition and autoignition temperatures may be combusted in a less severe oxidation environment (lower temperature and less excess oxygen) than those materials with a high flammability limit, high flash point and high ignition and autoignition temperatures. The flash point and upper and lower flammability limits of some of the pure compounds found on the hazardous waste listing are presented (Table 1).[1456] The autoignition temperatures of some of the common organic compounds are also presented (Table 2).[0285]

Combustion Temperature. Of the "three T's" of good combustion, time, temperature and turbulence, only the temperature may be readily controlled after the incinerator unit is constructed. This can be done by varying the air/fuel ratio. If solid carbonaceous waste is to be burned without smoke, a minimum temperature of 1,400 F must be maintained in the combustion chamber. Upper temperature limits in the incinerator are dictated by the refractory materials available. Whenever a temperature of 2,400 F is exceeded, special refractories are required. A design range of 1,800 to 2,000 F is usually desirable, unless thermodynamic equilibrium considerations dictate some other temperature requirement. The rates of most combustion reactions increase rapidly with increases in temperature, while a few peak at relatively low values. The latter are rare but must not be overlooked when unusual fuels are burned.[0304]

TABLE 1

COMBUSTIBILITY CHARACTERISTICS OF PURE GASES AND VAPORS IN AIR[1456]

Gas or Vapor	Lower Limit Percent by Volume	Upper Limit Percent by Volume	Closed Cup Flash Point Fahrenheit
Acetaldehyde	4.0	57	- 17
Acetone	2.5	12.8	0
Acetylene	2.5	80	-
Allyl alcohol	2.5	-	70
Ammonia	15.5	26.6	-
Amyl acetate	1.0	7.5	77
Amylene	1.6	7.7	-
Benzene (benzol)	1.3	6.8	12
Benzyl chloride	1.1	-	140
Butene	1.8	8.4	-
Butyl acetate	1.4	15.0	84
Butyl alcohol	1.7	-	-
Butyl cellosolve	-	-	141
Carbon disulfide	1.2	50	- 22
Carbon monoxide	12.5	74.2	-
Chlorobenzene	1.3	7.1	90
Cottonseed oil	-	-	486
Cresol m or p	1.1	-	202
Crotonaldehyde	2.1	15.5	55
Cyclohexane	1.3	8.4	1
Cyclohexanone	1.1	-	111
Cyclopropane	2.4	10.5	-
Cymene	0.7	-	117
Dichlorobenzene	2.2	9.2	151
Dichloroethylene (1, 2)	9.7	12.8	57
Diethyl selenide	2.5	-	57
Dimethyl formamide	2.2	-	136
Dioxane	2.0	22.2	54
Ethane	3.1	12.5	-
Ether (diethyl)	1.8	36.5	- 49
Ethyl acetate	2.2	11.5	28
Ethyl alcohol	3.3	19.0	54
Ethyl bromide	6.7	11.3	-
Ethyl cellosolve	2.6	15.7	104
Ethyl chloride	4.0	14.8	- 58
Ethyl ether	1.9	48	- 49
Ethyl lactate	1.5	-	115
Ethylene	2.7	28.6	-
Ethylene dichloride	6.2	15.9	56
Ethyl formate	2.7	16.5	- 4
Ethyl nitrite	3.0	50	- 31
Ethylene oxide	3.0	80	-
Furfural	2.1	-	140

TABLE 1

COMBUSTIBILITY CHARACTERISTICS OF PURE GASES AND VAPORS IN AIR[1456] - CONTINUED

Gas or Vapor	Lower Limit Percent by Volume	Upper Limit Percent by Volume	Closed Cup Flash Point Fahrenheit
Gasoline (variable)	1.4 - 1.5	7.4 - 7.6	- 50
Heptane	1.0	6.0	25
Hexane	1.2	6.9	- 15
Hydrogen cyanide	5.6	40.0	-
Hydrogen	4.0	74.2	-
Hydrogen sulfide	4.3	45.5	-
Illuminating gas (coal gas)	5.3	33.0	-
Isobutyl alcohol	1.7	-	82
Isopentane	1.3	-	-
Isopropyl acetate	1.8	7.8	43
Isopropyl alcohol	2.0	-	53
Kerosene	0.7	5	100
Linseed oil	-	-	432
Methane	5.0	15.0	-
Methyl acetate	3.1	15.5	14
Methyl alcohol	6.7	36.5	52
Methyl bromide	13.5	14.5	-
Methyl butyl ketone	1.2	8.0	-
Methyl chloride	8.2	18.7	-
Methyl cyclohexane	1.1	-	25
Methyl ether	3.4	18	-
Methyl ethyl ether	2.0	10.1	- 35
Methyl ethyl ketone	1.8	9.5	30
Methyl formate	5.0	22.7	- 2
Methyl propyl ketone	1.5	8.2	-
Mineral spirits #10	0.8	-	104
Naphthalene	0.9	-	176
Nitrobenzene	1.8	-	190
Nitroethane	4.0	-	87
Nitromethane	7.3	-	95
Nonane	0.83	2.9	88
Octane	0.95	3.2	56
Paraldehyde	1.3	-	-
Paraffin oil	-	-	444
Pentane	1.4	7.8	-
Propane	2.1	10.1	-
Propyl acetate	1.8	8.0	58
Propyl alcohol	2.1	13.5	59
Propylene	2.0	11.1	-
Propylene dichloride	3.4	14.5	60
Propylene oxide	2.0	22.0	-
Pyridine	1.8	12.4	74
Rosin oil	-	-	266

TABLE 1

COMBUSTIBILITY CHARACTERISTICS OF PURE GASES AND VAPORS IN AIR[1456] - CONTINUED

Gas or Vapor	Lower Limit Percent by Volume	Upper Limit Percent by Volume	Closed Cup Flash Point Fahrenheit
Toluene (toluol)	1.3	7.0	40
Turpentine	0.8	-	95
Vinyl ether	1.7	27.0	-
Vinyl chloride	4.0	21.7	-
Water gas (variable)	6.0	70	-
Xylene (xylol)	1.0	6.0	63

TABLE 2

AUTOIGNITION TEMPERATURE OF SOME COMMON ORGANIC COMPOUNDS[0285]

Compound	Temperature F	Compound	Temperature F
Acetone	1000	Hydrogen	1076
Ammonia	1200	Hydrogen cyanide	1000
Benzene	1075	Hydrogen sulfide	500
Butadiene	840	Kerosene	490
Butyl alcohol	693	Maleic anhydride	890
Carbon disulfide	257	Methane	999
Carbon monoxide	1205	Methyl alcohol	878
Chlorobenzene	1245	Dichloromethane	1185
Cresol	1038	Methyl ethyl ketone	960
Cyclohexane	514	Mineral spirits	475
Dibutyl phthalate	760	Petroleum naphtha	475
Ethyl ether	366	Nitrobenzene	924
Methyl ether	662	Oleic acid	685
Ethane	950	Phenol	1319
Ethyl acetate	907	Phthalic anhydride	1084
Ethyl alcohol	799	Propane	874
Ethyl benzene	870	Propylene	940
Ethyl chloride	965	Styrene	915
Ethylene dichloride	775	Sulfur	450
Ethylene glycol	775	Toluene	1026
Ethylene oxide	804	Turpentine	488
Furfural	739	Vinyl acetate	800
Furfural alcohol	915	Xylene	924
Glycerin	739		

There are four basic methods of controlling the combustion temperature:

(1) Excess air control. The adiabatic flame temperature is a function of both the type of fuel and the amount of air (oxygen) used. For example, the adiabatic combustion temperatures* of a cellulose waste that occur with variations in the amount of excess air very dramatically (Figure 1), clearly indicating the importance of maintaining the proper air/fuel ratio when the maintenance of a specific temperature is required. Control is obtained through automatically controlled or strenuously supervised operation. The designer can provide limiting orifices, nozzles, or pumps to prevent overfiring during continuous feeding of liquids and gases. For liquid fuels the problem is aggravated as the volatility of the fuel increases. If an incinerator is fed with discrete amounts at intervals, the hourly sum of these amounts must not exceed the rated capacity, and the intervals between feeding must be regulated. The greater the volatility of the waste, the smaller these discrete amounts must be and the more frequent the feed intervals. To illustrate, one may toss a teaspoon of gasoline every minute on the backyard grill without creating havoc, but a pint of gasoline tossed at once can have disastrous effects. All too often, this simple fact is overlooked in incinerator operation.[0304]

(2) Radiant heat transfer. Most combustion processes exist for the purpose of heat transfer, however, this is not usually the case for incinerators. Some large municipal waste incinerators use heat transfer surface as a means to control temperature and this design practice is growing although it is seldom economically feasible for industrial incinerators. It should be considred, however, when economics might make it attractive. Radiation to the sky is feasible, and several designs are capable of doing this. Where either heat transfer surface or radiation to the sky is used, surface area relationships (Table 3) can be used to estimate the combustion temperature.[0304]

(3) Two-stage combustion. When the combustion is divided into two distinct steps and the first stage is supplied with a deficiency of air, the first stage can act as a gasifier for certain fuels while burning incompletely at reduced temperatures. A second stage is necessary to burn the combustible products produced in the first stage, and its temperature must be limited by either the first method discussed (excess air control) or by heat transfer. Incinerators of this type must be carefully engineered to assure proper ignition and complete burning in the second stage. Additionally, feed rates must be carefully

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* In practice, the actual temperatures will be less because of thermal conduction losses through the furnace walls, thermal radiation to cold surfaces and possible incomplete combustion of the waste.

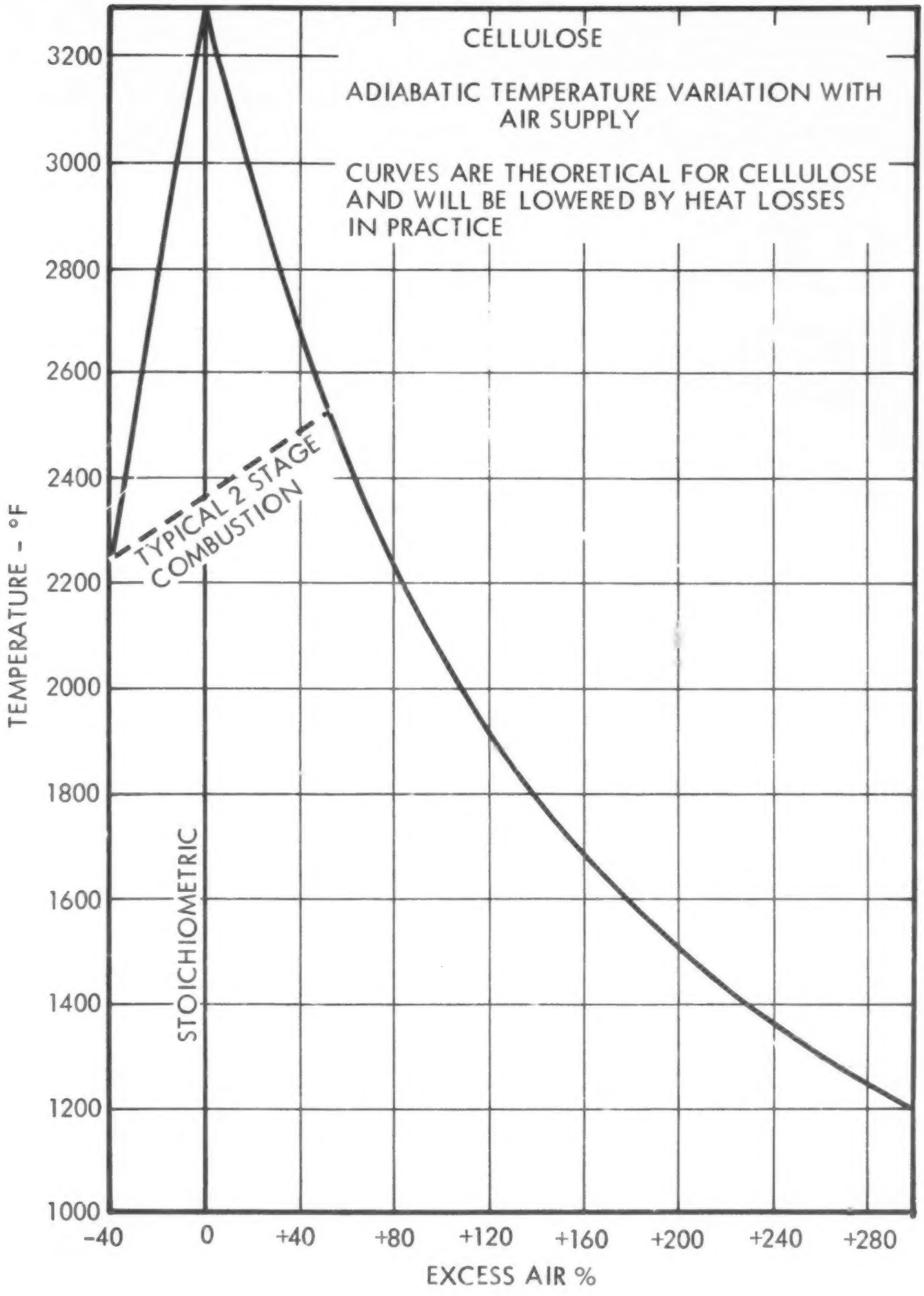

Figure 1. Adiabatic Temperature of a Cellulose Fuel Versus Excess Air.[0304]

TABLE 3

FURNACE TEMPERATURE VERSUS FIRING RATE[0304]

Fraction Cold (%)*	Firing Rate† Btu/hr sq ft	Furnace Temperature (°F)‡		
		0% Excess Air	50% Excess Air	100% Excess Air
0	Any	3677	2790	2230
10	10,000	2021	1839	1668
	40,000	2680	2303	1984
	80,000	2992	2482	2083
	120,000	3137	2563	2124
20	10,000	1709	1587	1470
	40,000	2349	2083	1844
	80,000	2680	2303	1984
	120,000	2866	2413	2047
30	10,000	1538	1442	1350
	40,000	2156	1942	1745
	80,000	2487	2178	1907
	120,000	2680	2303	1984
40	10,000	1422	1342	1265
	40,000	2021	1839	1668
	80,000	2349	2083	1844
	120,000	2544	2216	1930
50	10,000	1336	1266	1199
	40,000	1918	1758	1606
	80,000	2243	2004	1791
	120,000	2437	2144	1884
60	10,000	1268	1206	1146
	40,000	1836	1691	1554
	80,000	2156	1942	1745
	120,000	2349	2083	1844
80	10,000	1165	1114	1064
	40,000	1709	1587	1470
	80,000	2021	1839	1668
	120,000	2212	1984	1775
100	10,000	1059	1045	1001
	40,000	1613	1507	1404
	80,000	1918	1758	1606
	120,000	2106	1904	1717

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*- Fraction Cold is the ratio of the surface of the furnace enclosure that receives heat divided by the total furnace surface.

†- Firing Rate is the ratio of the heat release in Btu/hr divided by the sum of all enclosing surfaces.

‡- Table is theoretical for conditions given and is computed with No. 6 fuel oil.

controlled since a decrease in the waste feed rate without a corresponding decrease in the air feed rate would result in the first stage progressively moving toward complete combustion with progressively higher combustion temperatures.[0304]

(4) Direct heat transfer. When heat-absorbing materials or other fuels are added to the waste fuel the temperature of combustion can be controlled. The most common method of achieving lower temperatures is to add water to the fuel since each pound of water added absorbs approximately 1000 Btu for evaporation and 1/2 Btu for every degree F of temperature rise as sensible heat content. The water may be added with the fuel or sprayed into the combustion zone if carefully controlled to avoid quenching the fire or damaging the refractory. Temperature may be increased by burning other fuels with the waste stream.[0304]

Recommended minimum temperature requirements for complete combustion of those candidate waste stream constituents applicable to incineration and requiring National Disposal Site treatment are presented in the profile reports discussing the individual constituents.

Combustion Zone Turbulence. The degree of turbulence (intimate mixing) of the air for oxidation with the waste fuel will affect the incinerator performance significantly. In general, either mechanical or aerodynamic means are utilized to achieve the intimate scrubbing and mixing of the air and fuel. The completeness of combustion and the time required for complete combustion are significantly affected by the amount and the effectiveness of the flame turbulence. There is no accepted parameter that will quantitatively define an amount of turbulence, therefore it is judged by the combustion results that are produced.

Turbulence may be created in the combustion zone mechanically and aerodynamically. Turbulence can be induced mechanically through the use of fixed and moving grates, rotary kilns, mechanical pokers and hand pokers. There are two design factors which must be considered before applying mechanical turbulence producers. First, they depend principally upon natural factors to clear away gaseous combustion products and bring in fresh oxygen. The primary function of mechanical turbulence producers is the removal of noncombustible coverings (ash) to expose unburned material. Second, if mechanical devices are metal, they must be protected from elevated combustion temperatures. This protective cooling can usually be achieved by circulating either air or water through the device.[0304]

Aerodynamic turbulence can be defined as; the creation of turbulence by gases in motion. High velocity jets of forced air can create a degree of turbulence that approaches perfection. The turbulence may be produced with convergent nozzles using air or steam, or it may be produced by air registers. Air registers are vane arrangements, usually circular, that surround a fuel injection nozzle. They serve as multiple nozzles both to increase the incoming air velocity and to create a forced vortex around the fuel nozzle. It should be pointed out that for fixed nozzle and vanes, and sometimes for variable ones, the degree of turbulence is almost always at its maximum with the maximum air flow. For this reason best results are often obtained if the incinerator is fired at its maximum rating. Shorter firing periods at maximum rate may produce better results than continued operation at low firing rates.[0304]

Another form of aerodynamic turbulence is achieved in the fluidized bed. Air is forced vertically through a bed of solids (usually cylindrical) at a rate that expands the bed without excessive solids carry-over. If the bed container is lined with refractory and the bed material is: (1) uniform and (2) does not fuse at the operating temperatures, excellent turbulence is created. Uniformity can be helped by utilizing a permanent bed of sand. By injecting new material at the rate of consumption, the bed is held level and the air-flow resistance held constant. Since solid fuels without appreciable ash (coke) can be added, the fluidized bed has found some application with waste solids that require auxiliary fuel.[0304]

Residence Time in the Combustion Zone. The third major requirement for good combustion is time. Sufficient time must be provided to the combustion process to allow slow-burning particles or droplets to completely burn before they are chilled by contact with cold surfaces or the atmosphere. The amount of time required depends on the temperature, fuel size and degree of turbulence achieved. Although it is customary to specify certain furnace volumes for heat releases in an attempt to obtain proper combustion times, this method is now generally recognized as inadequate. In the absence of specific data, combustion chambers with heat releases of 20,000 to 60,000 Btu/cu ft-hr are common. These values are very conservative for high performance burners, and the use of small compact incinerators means lower investment and lower maintenance. The evaluation of the factor of time can be made only by tests of individual burners and furnaces. Important information on this subject can be obtained directly from burner manufacturers. When slow-burning items are present, such as carbon particles or carbon monoxide, additional chambers (secondary combustion chambers) may be needed to allow time for complete combustion.[0304]

Recommended minimum residence time requirements for complete combustion of those candidate waste stream constituents applicable to incineration and requiring National Disposal Site treatment are presented in the profile reports discussing those individual constituents.

Incinerator System Selection

In order to determine the proper type of incinerator system (i.e., storage facility, incinerator, and effluent purification equipment) for use in a particular waste disposal situation, certain basic information about the waste material must be known (Table 4.).

Waste Toxicity. The toxicity of the waste material and its combustion products dictates the safety procedures, safety equipment and monitoring equipment required for personnel safety. For instance, an extremely toxic material might require remote operation of all processing units and the wearing of protective clothing, masks and self-contained breathing apparatuses by all operators in the vicinity of the incineration unit. Equipment to monitor combustion temperature and/or effluent compound concentration might be utilized in series with feed regulating equipment to ensure total combustion of the toxic material. The overall ability of the disposal system (storage facilities, transport equipment, incinerator, secondary abatement equipment and stack) to maintain low toxic contaminant concentrations at ground level could be determined through periodic or constant monitoring in and around the disposal facility.

TABLE 4

BASIC DATA CONSIDERATIONS WHEN CHOOSING A WASTE DISPOSAL SYSTEM[0304]

Type (s) of waste	Liquid, solid, gas, or mixtures.
Ultimate analysis	Carbon, hydrogen, oxygen and nitrogen, water, sulfur, and ash on an "as-received" basis.
Metals	Calcium, sodium, copper, vanadium, etc.
Halogens	Bromides, chlorides, fluorides.
Heating Value	BTU/lb on an "as-received" basis.
Solids	Size, form and quantity to be received.
Liquids	Viscosity as a function of temperature, specific gravity and impurities.
Gases	Density and impurities.
Special characteristics	Toxicity and corrosiveness, other unusual features.
Disposal rates	Peak, average,minimum (present and future).

Disposal Rate and Waste Corrosiveness. Regardless of the type of waste to be incinerated, the disposal rate determines the size and number of incinerators (as well as storage equipment) needed to combust a given waste stream. The waste stream's corrosiveness determines the materials of construction required in both the incineration unit and materials handling equipment. Incineration systems may be fabricated from a wide variety of construction materials. The selection of construction materials depends upon several factors: (1) corrosion, (2) strength, and (3) temperature. Most incinerators are constructed of carbon steel material and are lined with appropriate alumina refractory to withstand the temperatures of the incineration process. Some catalytic units, however, as well as some thermal incinerators are fabricated without refractory, using only high-temperature stainless steel. The advantage of this approach is the elimination of the refractory, which will eventually need refurbishing or replacement. More costly materials such as Inconel, Incoloy, or Hastelloy are normally utilized only when the waste is corrosive to other materials.[0285]

Refractories used in incineration systems are generally of the alumina type. Standard or super duty firebrick backed up by insulting brick is suitable in most cases. Castable refractories are also widely used. In short, the refractories, which are used for most incineration applications are equivalent to those which would be used for high-temperature furnaces.

Secondary Abatement Requirements. Many wastes which lend themselves to incineration cannot be incinerated without some secondary form of treatment, due to the production of compounds which might be toxic in nature and therefore cannot be released to the atmosphere. Normally these wastes can be divided into three categories:

(1) waste which contains inorganic salts;

(2) waste which contains halogen compounds;

(3) waste which contains sulfur compounds.

Those which contain inorganic salts will produce the oxide of the metal ion of that salt upon combustion. The commonest inorganic metal ion is sodium, although potassium, or for that matter any other metal ion, may be found in the waste. The oxide which is formed in the combustion reaction usually will be in a finely divided form and will require subsequent removal by either mechanical methods or wet scrubbing. This type of product usually requires a high-energy scrubber of the venturi type.

The halogen ions most commonly found in wastes are generally chlorine and fluorine, which are often part of halogenated hydrocarbons. Complete combution of the organic portion of the waste may result in the production of chlorine or fluorine in the products of combustion. These are relatively insoluble in water and therefore cannot be removed by wet scrubbing as long as they are in this form. This type of waste should first be analyzed to determine the amount of hydrogen present, since the hydrogen will react with the halogen forming the halogen acid. If there is not sufficient hydrogen in the waste material to accomplish complete conversion of the halogen to the halogen acid, the conversion must be accomplished by injection of additional hydrogen in the form of natural gas or other combustible. Once the halogen has been converted to the acid gas, it may be satisfactorily removed in a wet scrubber. Here the low-energy or packed tower type of scrubber is satisfactory. For example, if trichloroethylene is a major component in a waste effluent, it can be incinerated in accordance with the following reaction:

$$CHClCCl_2 + 2O_2 \longrightarrow 2\ CO_2 + HCl + Cl_2$$

While the hydrogen chloride which is formed in this reaction can be removed by scrubbing with water, the chlorine, which is relatively insoluble, will pass through the water and into the atmosphere. By the addition of natural gas or another hydrocarbon fuel, all the chlorine can be converted to hydrogen chloride as follows:

$$CHClCCl_2 + 7/2\ O_2 + CH_4 \longrightarrow 3\ CO_2 + 3HCl + H_2O$$

The hydrogen chloride formed in this reaction can be removed in a wet scrubber. In this particular case, natural gas or other auxiliary fuel would be required for combustion because of the low calorific value of the trichloroethylene.[0285]

Sulfur compounds are often found in wastes either as part of a sulfonated organic molecule or in the form of sulfates or sulfides. Complete combustion of these wastes with air results in SO_2 formation. Complete removal of SO_2 can be handled by caustic scrubbing or a number of more complicated processes designed ultimately to recover sulfur.

One pollutant, NO, is common to all incineration processes which utilize air as the oxidant source (as opposed to pure oxygen or some other oxidant which contains no nitrogen). The NO formation is the result of the oxygen and nitrogen from the air reacting at the elevated flame temperature present in incinerators. The thermodynamic equilibrium concentrations of NO present in combustion effluent streams as a function of flame temperature and excess air have been determined[0304] and are presented graphically (Figure 2). Generally industrial incineration operations do not abate NO emissions. There are currently abatement techniques available but they involve catalytic or thermal reduction (requiring a reductant such as CH_4 or H_2) of NO to N_2 followed by thermal oxidation of excess reductant.[1435] These processes are capable of reducing NO_x concentrations in the stack effluent to the 50 ppm level.[1435] It is the reductant cost plus the catalyst cost (when a catalyst is used) which makes application of this type of abatement process economically unattractive in most situations.

The specific types of abatement equipment are discussed in detail in the Appendix of this report. Their operating principles, characteristics and general applications are delineated. It should be noted that when applied to treatment processes handling hazardous waste constituents, a high degree of efficiency is of primary concern as opposed to economic considerations. Therefore, the types of equipment most likely to be utilized in conjunction with incineration facilities at National Disposal Sites are packed bed scrubbers (both fixed and floating bed types), venturi scrubbers, electrostatic precipitators, and fabric filters.

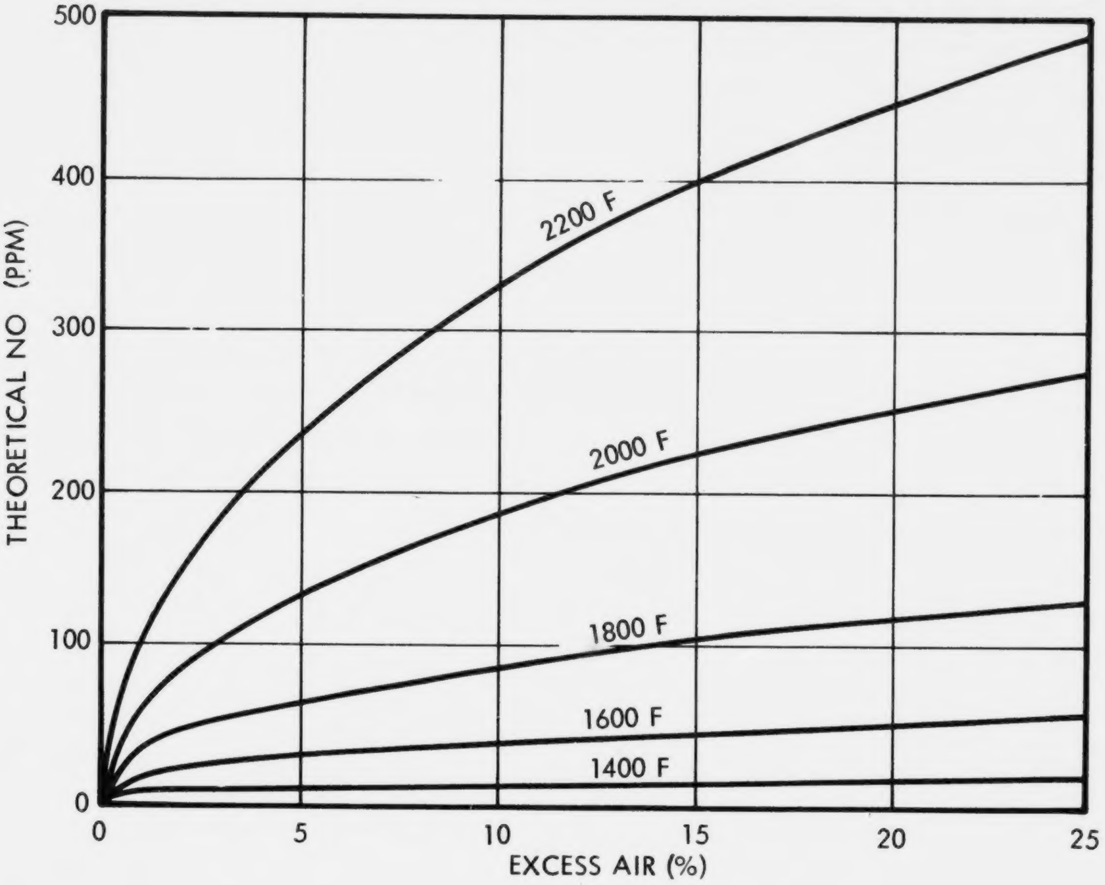

Figure 2. Equilibrium Nitric Oxide Concentrations in Combustion Effluents.0304

Steam Plume Generation. Another problem common to most incineration processes is that of steam plume generation. The appearance of a steam plume has a very important psychological implication which must be considered. An incinerator process effluent may contain no harmful pollutants, however, the presence of combustion product water plus any moisture picked up in scrubbing operations will cause the stack effluent to show a steam discharge plume upon becoming saturated with moisture. Although the steam will have no deleterious effects on the surrounding area, its appearance may cause concern with the public that the air cleaning equipment is inadequate or malfunctioning.

Steam plumes are the result of rapid cooling of moisture containing gases to below their saturation temperature. Gases from wet scrubbers will quickly show a steam plume at the stack discharge. During the cold winter months, the gases are subjected to a colder atmosphere and are thus air-condensed sooner and have shorter plume trails compared with equivalent gases cooled by the summer atmosphere.

As a guide, saturated gases which discharge from the stack below 105 F will have a negligible appearance and will not create a questionable steam plume. At 105 F the volume of moisture content is less than 7 percent, whereas at higher saturation temperatures, the percentage of moisture by volume is as follows: 130 F, 15.0 percent; 160 F, 32.5 percent; 180 F, 51.0 percent.[0285]

In addition to appearance, steam plumes have other side effects which include:

(1) SO_2 (or other corrosive gases) may be absorbed by the newly formed droplets, forming sulfurous acid and then fall on homes and industrial sites.

(2) In some cases odoriferous constituents may be entrapped by falling droplets to increase odor at ground elevation.

There are three basic methods for steam plume minimization.^{0285}

(1) Indirect Cooling of Hot Gases

Cooling is effected within a continuous S shaped duct with surface exposure for radiation and cooling by atmospheric air surrounding the ducts. Often the ducts may be arranged essentially vertically with U bends and should be furnished with cleanout doors and hoppers to permit intermittent dust removal. The addition of fans, handling large quantities of atmospheric air, blowing or inducing air across banks of ducts which transport the uncleansed gas, has recently been introduced.

(2) Sensible or Direct Cooling of Saturated Gases

This technique cools already 100 percent saturated gases with cool water. Sufficient coolness is required to dehumidify or condense water vapor down to the desirable lower saturation. By using a standard spray tower cooling water at 70 to 85 F may be introduced at 25 psig. Droplets will fall counterflow to the gas passage and carry away latent heat of the water vapor and sensible heat of the dry gas. As a general rule, the cool water leaving a properly designed tower will approach within 10 or 15 F of the entrance gas temperature. Therefore, pounds of 80 F water needed equals 3.51 lb water/lb dry gas or 0.42 gal/lb dry gas. Use of a tower filled with drip-point grid tiles offers a method to obtain benefit of maximum heat transfer with an approach of approximately 5 F or less (between the gas and liquid discharging).

(3) Cooling by Mixing with Atmospheric Air

In some special cases sensible cooling may be obtained by the addition of atmospheric air having a low dew point temperature. However, this method becomes impractical where already large saturated volumes of gas having high saturation temperatures are involved.

Gaseous Waste Incineration. The type and form of waste will dictate the type of combustion unit required. A number of control methods have been successfully developed for applications where the pollutants are in the form of fume or gas. If the waste gas contains organic materials which are combustible, then incineration should be considered as a final method of disposal. Direct flame, thermal, or catalytic oxidation of such wastes can produce an effluent of carbon dioxide, nitrogen, and water vapor which can be vented safely to the atmosphere. Economic considerations are paramount in the selection of incineration systems because of the high fuel costs when concentrations of organic constituents are low.

Direct flame incineration is used normally with materials which are at or near their lower combustibility limit. In a well-designed commercial combustor or burner, gases having heating values as low as 100 Btu/cu ft can be burned without auxiliary fuel. Gases having even lower heating values, which are preheated to 600 or 700 F, often will sustain combustion without help from auxiliary fuel. Hydrogen cyanide, which is an extremely toxic gas, may be burned in air; carbon monoxide, which is also a deadly gas and a by-product of many partial combustion reactions, can be burned in this manner. Solvent vapors mixed in high quantities with air may produce a combustible mixture which can be burned in a conventional forced draft combustion system.

When the amount of combustible material in the mixture is below the lower flammable limit, it may be necessary to add small quantities of natural gas or other auxiliary fuel to sustain combustion in the burner. But in either case, whether the material burns with or without the assistance of auxiliary fuel, combustion occurs at high temperatures (about 2,500 F), good mixing is achieved with the oxygen in the air, and the resultant products of combustion generally are carbon dioxide, nitrogen, and water vapor. Here the contaminant, whether it is a solvent vapor or pure gas, is serving as a part of the fuel. It is contributing a significant portion of the total heat released to the system and can be burned with a minimum of auxiliary fuel and therefore a minimum of operating cost. Direct flame combustion should be employed only where the amount of auxiliary fuel needed to sustain combustion is low and where the contaminant supplies at least 50 percent of the fuel value of the mixture.[0285]

Equipment for direct flame incineration may be a conventional industrial burner or combustor and combustion chamber (either forced or induced draft), or it may be a flare type burner as found in many petroleum refineries and petrochemical plants. A detailed discussion of the individual processing units will be presented in Section 2 of this process evaluation.

Most waste gas incineration problems involve mixtures of organic material and air in which the amount of organic material is very small. This means that if it were injected directly through a burner, along with auxiliary fuel such as natural gas, the amount of natural gas required to achieve complete combustion would be quite high. Most conventional industrial burners require temperatures of 2,200 F or greater to sustain combustion, whereas thermal incineration can be carried out at much lower temperatures, sometimes as low as 900 F, but generally between 1,000 and 1,500 F.

Weak mixtures of organic material and air will usually have very low heating values, on the order of 1 to 20 Btu/cu ft. Some of the most common applications may be found in drying ovens which drive off a solvent or plasticizer in low concentrations in air, or form lithographing ovens or other process drying operations. Here it is more economical to heat a combustion chamber, using a conventional fuel in an industrial burner, and inject the contaminated air into this chamber just downstream from the burner flame, or even into the burner flame. Usually the waste gas is essentially air and therefore contains enough oxygen to complete combustion of the organic contaminant. But in some cases, where sufficient oxygen is not present in the fume, it can be added by means of a fan or blower, either by premixing with the fume or by injecting into the secondary combustion chamber along with the fume.[0285]

Incineration systems for thermal oxidation of gaseous wastes are of many different types and forms. Some utilize "line" burners when the fume contains sufficient oxygen for its own combustion. Here the waste gas passes over and through the flame of the "line" burner in a refractory lined duct. Other systems utilize an external burner, either natural, forced draft, or aspirating type. In this system the flame passes into the duct from the burner mounted in the duct wall, causing turbulence in the chamber, and the contaminated air passes through and around the flame and is heated to the reaction temperature. Such units may be vertical or horizontal and may be induced or forced draft, depending upon the physical arrangement most desirable for the system.[0285]

Catalytic incineration is applied to gaseous wastes containing low concentrations of combustible materials and air. Usually noble metals such as platinum and palladium are the catalytic agents. A catalyst is defined as a material which promotes a chemical reaction without taking a part in it. The catalyst does not change nor is it used up.

These catalysts must be supported in the hot waste gas stream in a manner that will expose the greatest surface area to the waste gas so that the combustion reaction can occur on the surface, producing nontoxic effluent gases of carbon dioxide, nitrogen, and water vapor. Since most waste gases from ordinary industrial processes are at low temperatures up to 300 F, a preheat burner is required to bring these gases up to the reaction temperature.[0285]

The advantage of the catalyst is that the reaction temperature in catalytic systems is lower than it is in thermal systems because the catalyst promotes the reaction at a lower temperature. Most catalytic reactions can be carried out at preheat temperatures between 600 and 1,000 F. This of course results in a fuel saving when compared with thermal systems but involves a much higher initial investment because of the catalyst cost. Catalytic incinerators usually operate at or below 25 percent of the LEL (lower explosive limit) of the material in the waste gas and below the normal oxidation temperature of the contaminant. Care should be taken, however, when analyzing the waste for catalytic combustion, that the waste gas contains a low enough concentration of the contaminant to prohibit burnout of the catalyst. Most catalysts are suitable for maximum operating temperatures of 1,500 to 1,600 F. A high concentration of contaminant in the waste gas, even with minimal preheat, may release enough heat on the surface of the catalyst to cause catalyst burnout. Therefore, catalytic systems are most applicable to low concentrations of contaminants where the temperature rise across the catalyst will be on the order of several hundred degrees.[0285]

Catalytic systems have been used widely in the oxidation of paint solvents, odors arising from chemical manufacture, food preparation, wire enameling ovens, lithographing ovens, and similar applications.

Catalyst systems are susceptible to poisoning agents, activity suppressants and fouling agents. These compounds appear as contaminants in the waste gas stream and are specific for different types of catalysts. Catalyst manufacturers can usually state which compounds are detrimental to the operation of specific catalysts. It is therefore necessary to know what contaminants are present in a waste gas stream prior to the selection of an efficient catalytic combustion system.[146]

Liquid Waste Incineration. Incineration is one possibility for the destruction of liquid wastes. Liquid wastes may be classified into two types from a combustion standpoint: (1) combustible liquids, and (2) partially combustible liquids. Noncombustible liquids cannot be treated or disposed of by incineration. The first category would contain all materials having sufficient calorific value to support combustion in a conventional combustor or burner. The second category would include materials that would not support combustion without the addition of auxiliary fuel and would have a high percentage of noncombustible constituents such as water. A partially combustible waste may also contain material dissolved in the liquid phase which, if inorganic in nature, will form an inorganic oxide upon combustion and require secondary collection prior to atmospheric release.

Assuming that either of these types of wastes is primarily organic in nature, even though the quantity of the organic material may be small, incineration of such materials becomes essentially a straightforward combustion problem in which air must be mixed with the combustible at some temperature above its ignition temperature. When starting with a waste in liquid form, it is necessary to supply sufficient heat for vaporization in addition to raising it to its ignition temperature.

liquids vaporize and react more rapidly when finely divided in the form of a spray, atomizing nozzles are usually employed to inject waste liquids into incineration equipment whenever the viscosity of the waste permits atomization. There are many wastes which might be classified liquid which are hardly liquid in nature. Slurries, sludges, and other materials of high viscosity can be handled only in special types of incineration systems.[0285]

In order that a liquid waste may be considered combustible, there are several rules of thumb which should be used. The waste should be pumpable at ambient temperatures or capable of being pumped after heating to some reasonable temperature level. The liquid must be capable of being atomized under these conditions. If it cannot be pumped or atomized, it cannot be burned as a liquid but must be handled as a sludge or solid. Liquid waste incineration generally involves liquids having viscosities up to approximately 1,000 SSU, although lower viscosities are desirable.

In order to be considered a combustible liquid waste, the material must sustain or support combustion in air without the assistance of an auxiliary fuel. This means that the waste will generally have a calorific value of 8,000 to 10,000 Btu/lb or higher. Below this calorific value, the material would not exhibit properties which would enable it to maintain a stable flame in a commercial combustor or burner. Materials which fall into this category (>8,000 Btu/lb) are light solvents (such as toluene, benzene, acetone, ethyl alcohol) and heavy organic tars and still bottoms similar to residual fuel oil. The wastes may be combinations of both, which would give a mixture having an intermediate viscosity and heating value. These wastes come from cleaning operations in chemical plants and refineries or are the residues from distillation processes and are usually not recovered for economic reasons.[0285]

The equipment which is used to incinerate combustible liquid waste can also vary from manufacturer, but its basic form will be that of a combustor or burner designed to handle a liquid waste through a steam, air, or mechanical atomizing nozzle. High heat release combustors require minimal secondary incineration chambers, but usually incineration is carried out in combustion chambers having volumes which provide for a heat release of 25,000 Btu/hr-cu ft of combustion volume. Residence times within an incinerator burning liquid waste will vary from 0.5 to 1 sec. The combustion chamber is usually cylindrical in shape and may be used in a vertical or horizontal arrangement. The vertical chamber has the advantage that the incinerator acts as its own stack, but obviously it is not well adapted to a tall stack arrangement. Horizontal incinerators can be more easily connected to tall chimneys or stacks.[0285] Some specially designed rotary kilns have been applied to the disposal of liquid chemical warfare agents. Highly explosive wastes (wet machining wastes from munitions manufacturing) are currently disposed of by open burning. A detailed description of these systems will be provided later in the report.

Many combustible liquid wastes can be utilized as fuel for a boiler, air preheater, or other heat recovery device which can turn the waste heat energy from the incineration system into profit. Heat recovery devices, however, are advisable only when the amount of heat recovered and the cost of the recovery equipment can be economically justified. If the waste liquid should contain noncombustibles such as inorganic salts, or materials which would be converted into corrosive compounds in the combustion reaction, such as chlorides or fluorides, then heat recovery is usually incompatible and should not be considered.

Liquid wastes having a heating value of below 8,000 Btu/lb can be considered in the partially combustible category. It must again be emphasized that this is a rule of thumb and that some materials as high as 10,000 or 11,000 Btu/lb will not sustain combustion by themselves. It is also important with this type of waste that the material handling method be compatible with the equipment selected. Viscosities should be reduced to the point where the material is pumpable and atomizable at either ambient or slightly elevated temperatures.

Waste material in this classification is often aqueous in nature, consisting of organic compounds miscible with water. Such waste may also contain sulfur compounds, phosphorus compounds, or combinations of organic and noncombustible inorganics. These materials may have enough organic content to exhibit visible combustion in a high temperature furnace, or they may be so low in combustible material that no visible combustion is apparent.

There are several basic considerations in the design of an incinerator for a partially combustible waste. First, the waste material must be atomized as finely as possible to present the greatest surface area for mixing with combustion air. Second, adequate combustion air to supply all the oxygen required for oxidation or incineration of the organics present should be provided in accordance with carefully calculated requirements. Third, the heat from the auxiliary fuel must be sufficient to raise the temperature of the waste and the combustion air to a point above the ignition temperature of the organic material in the waste. Unlike the combustible waste, which sustains combustion by itself, this waste may not always be injected through the combustor or burner but may rather be atomized into the secondary chamber. If the waste material is marginal in combustibility, it may be fed directly through the burner or combustor along with the auxiliary fuel. Temperatures of 2,200 to 2,700 F will result, complete combustion of the organic in the waste will occur, and the products of combustion can be vented to the atmosphere.

The equipment for handling this type of waste is usually a horizontal or vertical refractory lined cylindrical furnace with an auxiliary fuel burner firing at one end or tangential to the cylindrical shell. The size of the incinerator depends upon the heat release in the system and the amount of combustion air to be used. Mixing is accomplished by baffles or a checker wall, and the temperature of the incinerator should vary, depending on the type and the amount of the waste. In most cases, it is possible to incinerate most organic aqueous mixtures below 1,800 F and many in the range of 1,200 to 1,500 F. As with gaseous wastes, the autoignition temperature of the waste should first be determined, and the incinerator should be operated at a controlled temperature several hundred degrees above this point.[0285]

Incineration of wastes which are not pure liquids but which might be considered sludges or slurries is also an important waste disposal problem. Because sewage is handled in sludge form, many of the processes and equipment previously applied to handling sewage sludge have found application in the industrial disposal field. The combustion principles are the same, but the manner of achieving the combustion is different. Some of the types of incinerators which are applicable to this type of disposal problem are rotary kilns, multiple hearth furnaces and fluidized bed incinerators. A detailed discussion of the individual processing units will be presented in Section 2 of this process evaluation. Some of the various liquid waste materials which are currently incinerated are discussed by Jones[0534] (Table 5).

Solids Incineration. Solids incineration is not a total disposal method, because most solid materials contain noncombustibles and have residual ash. Municipal and industrial incinerators probably account for 30 to 50 percent of the total trash disposal within the United States at the present time. The object of any incinerator is to provide complete combustion of the material fed into it. The complications are, however, the wide variety of materials which must be burned. There is everything from wet garbage with a heating value of approximately 2,000 Btu/lb to such plastics as polystyrene, which have a heating value of approximately 19,000 Btu/lb. Controlling the proper amount of air to give good combustion of both materials is difficult, and with most currently available incinerator designs it is impossible.

TABLE 5

DESTRUCTION OF WASTES BY INCINERATION[0534]

Waste	Remarks
Liquid wastes from manuf. of ammonia, urea, nylon intermediates, ethylene glycol, methylamines, methacrylates	Wastes concentrated to 50% organic content-no auxiliary fuel required. Steam atomized burners
Organic tars, catalyst complexes	Metals must be collected when catalysts are burned.
Liquid Wastes containing hydrocarbons, high-boiling degradation products, tars from nylon intermediate manuf.	-
Liquid from acrylonitrile manuf. containing acetonitrile and cyanides + slop oils + phenolic resin wastes (inorganic)	Nitrile wastes have high fuel value. Provision for auxiliary fuel gas was made, 1600 F.
Two soot streams from acetylene manuf.; still residues from acrylonitrile and vinyl chloride processing stripping steam with acrylonitrile.	Natural gas used as auxiliary fuel. Flow and organic content of waste fluctuates greatly, 1500 F
Heavy sludge acid, sulfonated tars from benzene plant. General refuse, scrap plastic.	Solid wastes fed first, then liquid.
Styrene still residues.	Mixed with fuel oil and used in heating furnaces.
Organic acids, salts, anhydrides, hydrocarbons and chlorinated hydrocarbons from manufacture of chlorinated organics.	Natural gas fuel used in a vortex burner. Wastes neutralized with ammonia prior to incineration to prevent corrosion.
Sludges containing oil, solids from separators, clarifiers, tank bottoms	Fluidized-bed furnace, 800-900 F
Biological sludges	-
Vent gases - H_2S, mercaptans	-
Spent caustic-50% phenols	Fuel oil used as auxiliary fuel
High-and low-boiling organics from nylon manuf.	-

Certain basic principles for complete combustion of solid waste with a subsequent low particulate emission from the combustion zone are as follows:[0285]

(1) Excess air: Air quantities should usually be kept on the order of 50 to 150 percent above the stoichiometric requirements.

(2) Minimum use of underfire air: This maintains low velocities and therefore reduces the particulate emission from the incinerator because it keeps small particles out of the gas stream.

(3) Proper use of overfire air: This provides ample oxygen and turbulence in the combustion space above the fuel bed. The overfire air injected into the system may be as high as 50 percent of the total required.

(4) Temperature: Temperature in the furnace space should be between 1400 and 1800 F to reduce the rate of smoke formation and odor. Temperatures below 1400 F will produce smoke and allow odor to escape from the incinerator. Above 1800 F there may be sintering or fusing of the ash with the furnace refractories. Excess air is used to control the furnace temperature.

(5) Sufficient combustion volume: The incinerator should have enough combustion volume to provide sufficient residence time for the burnout of all flying particulate matter. The average heat release per cubic foot of furnace volume should not exceed 25,000 Btu/cu ft-hr.

(6) Secondary chamber: A secondary chamber zone should be provided in every incinerator and, in fact, is required in most municipal and state codes now being adopted.

(7) Residence time: The residence time in the incinerator should be between 1 and 2 seconds.

(8) Reasonable loading rates: Low loading rates per square foot of grate surface should be adhered to, even in forced draft incinerators. They should be no more than 60 lb of waste/sq ft/hr.

Early solid waste incinerators were charged by a crane from a storage pit onto stationary grates. Some furnaces were hand stoked. Ash handling was arranged through undergrate hoppers in which the ash was water quenched and dumped into trucks and hauled away. Today, because of the awareness of air pollution problems, more modern designs have been developed. A variety of modern stokers (each best suited for a particular size and form of solid waste), which provide uniform and regular agitation of the feed, are used to feed the waste material onto the surface of the grate. The grate may be a fixed grate or a traveling grate system. Where the traveling grate is used, it is also considered part of the stoking apparatus.

The types of incinerators which are applicable to solid wastes are open-pit incinerators (when no secondary pollution problem exists) and closed incinerators such as retort and inline multiple chamber units, rotary kilns and multiple hearth incinerators.[0582] A detailed discussion of these units will be presented in Section 2 of this process evaluation.

The incinerator design does not have to be limited to a single combustible or partially combustible waste. Often it is both economical and feasible to utilize a combustible waste, either liquid or gas, as the heat source for the incineration of a partially combustible waste which may be either liquid or gas. Multiple or dual fuel burners for combustible wastes can be utilized in a single incineration chamber. Combination systems can often reduce the operating cost in terms of auxiliary fuel and should be carefully evaluated in the overall waste treatment program of any process plant. Heat recovery in these systems is applicable on an individual basis.

2. PROCESS DESCRIPTION

The following sections of this report will discuss in detail the operating principles, process applicability, process design, and process economics of each of the various types of incineration systems. As mentioned in the introduction of this evaluation, incinerators are generally classified by the form of waste which they burn. There are ten basic types of incinerator units, open pit incinerators, open burning, multiple chamber incinerators, multiple hearth incinerators, rotary kiln incinerators, fluizided bed incinerators, liquid combustors, catalytic combustors, gas combustors and stack flares. The type of waste for which each of these incineration units is best suited is detailed diagrammatically (Figure 3). The types of incinerator systems which are amenable to secondary abatement equipment application are also shown.

Fluidized Bed Incineration

Fluidized bed incinerators are versatile devices which can be used to dispose of solid, liquid and gaseous combustible wastes. The technique is a relatively new method for ultimate disposal of waste materials. It was first used commercially in the United States in 1962[0285] and has found limited use in the petroleum industry, paper industry and for processing nuclear wastes.[0582] In addition, applications of fluidized bed combustion to the disposal of sanitary sludge have been reported.[1465,1466]

Operating Principle. A typical fluidized bed incinerator is shown schematically (Figure 4). Air driven by a blower enters a plenum at the bottom of the combustor and rises vertically through a distributor plate into a vessel containing a bed of inert granular particles. Sand is typically used as the bed material. The upward flow of air through the sand bed results in a dense turbulent mass which behaves similar to a liquid. Waste material to be incinerated is injected into the bed where combustion occurs within the fluidizing media.

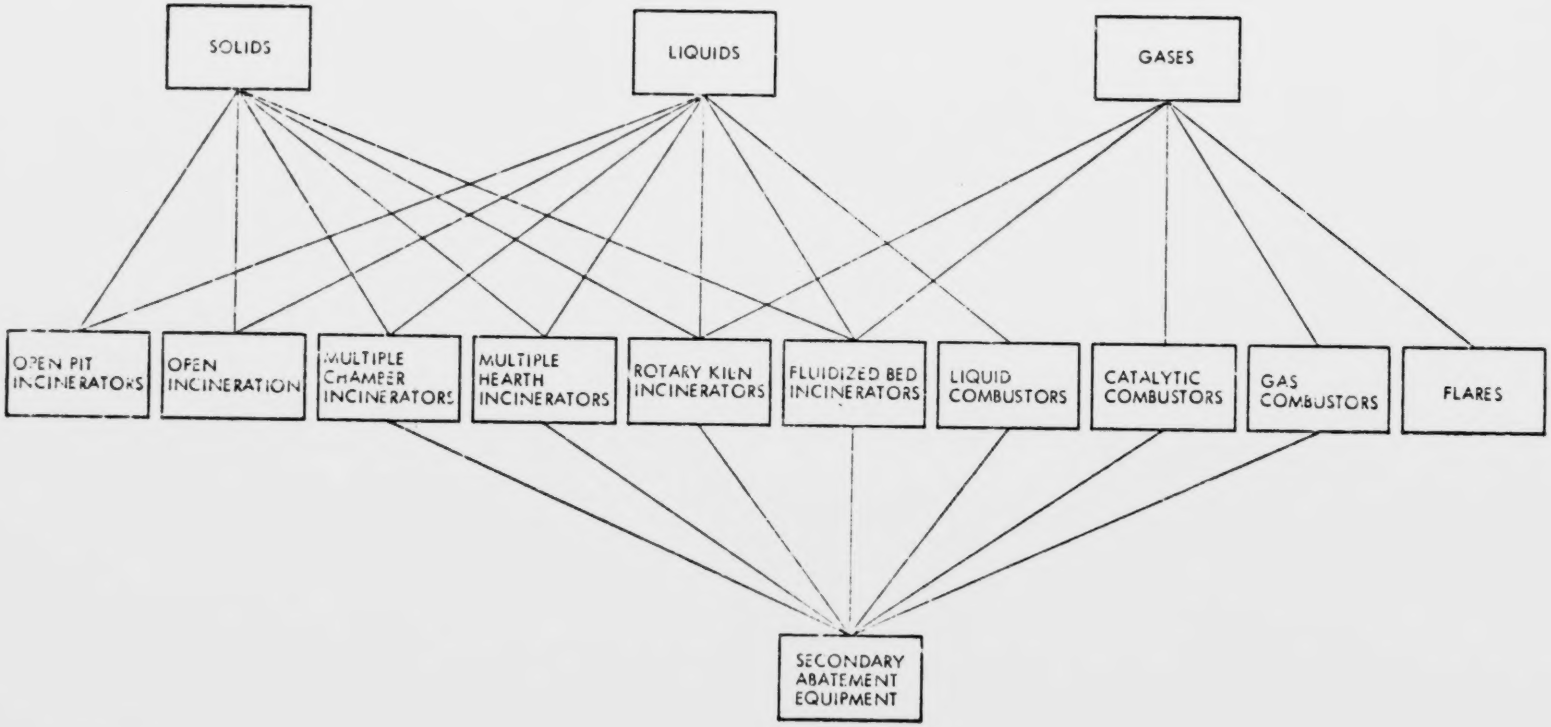
SOLIDS
LIQUIDS
GASES
OPEN PIT INCINERATORS
OPEN INCINERATION
MULTIPLE CHAMBER INCINERATORS
MULTIPLE HEARTH INCINERATORS
ROTARY KILN INCINERATORS
FLUIDIZED BED INCINERATORS
LIQUID COMBUSTORS
CATALYTIC COMBUSTORS
GAS COMBUSTORS
FLARES
SECONDARY ABATEMENT EQUIPMENT

Figure 3. Types of Incinerators and Their Applications

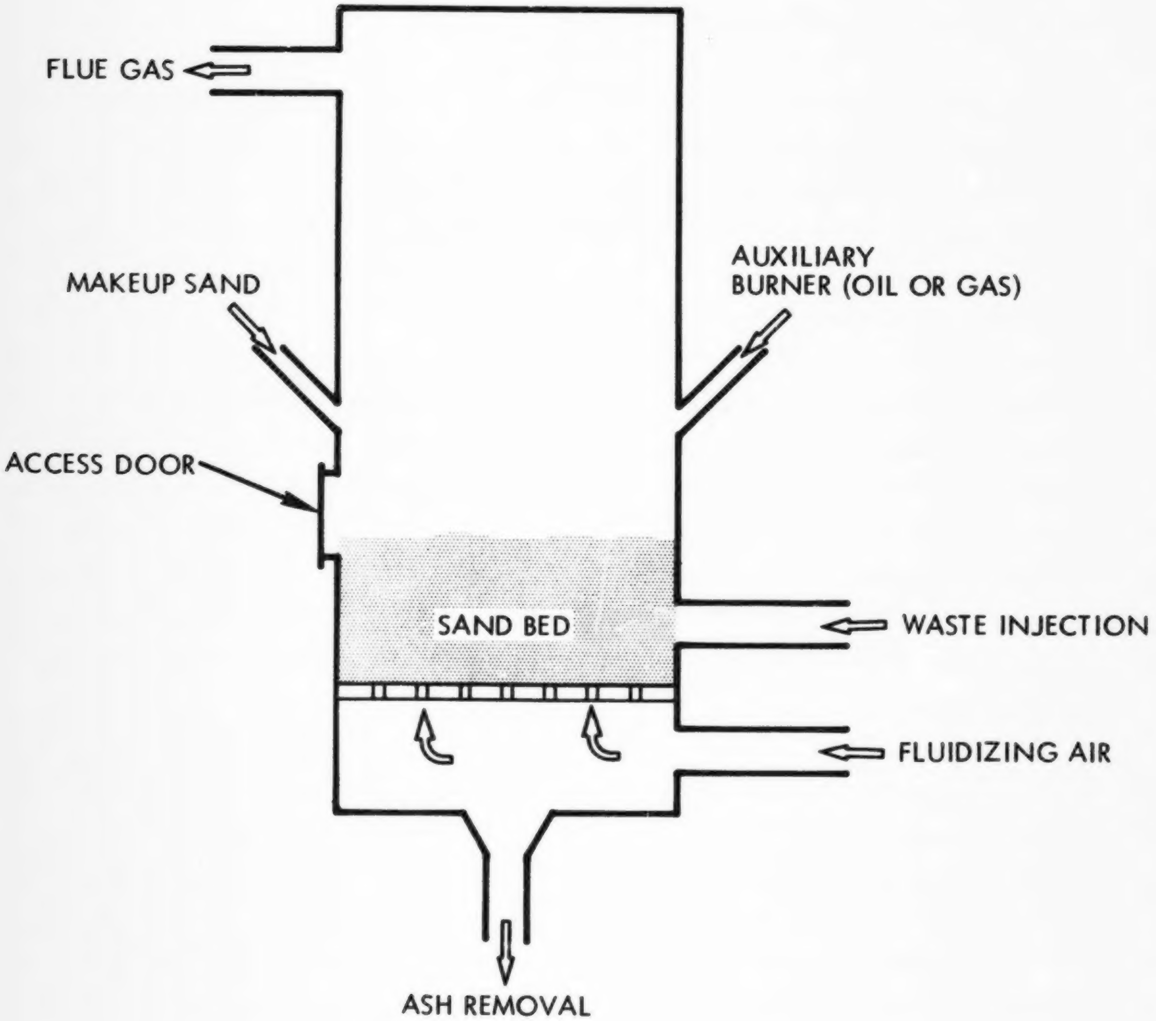
FLUE GAS
MAKEUP SAND
AUXILIARY
BURNER (OIL OR GAS)
ACCESS DOOR
SAND BED
WASTE INJECTION
FLUIDIZING AIR
ASH REMOVAL

Figure 4. Schematic of a Fluidized Bed Combustor

Air passage through the bed produces strong agitation of the bed particles. This promotes rapid and relatively uniform mixing of the injected waste material within the fluidized bed.

The mass of the fluidized bed is large in relation to the injected material. Bed temperatures are quite uniform and typically in the 1,400 to 1,600 F range. At these temperatures, heat content of the fluidized bed is approximately 16,000 Btu/ft^3 thus providing a large heat reservoir. By comparison, the heat capacity of flue gases at similar temperatures is three orders of magnitude less than a fluidized sand bed.

Heat is transferred from the bed into the injected waste materials to be incinerated. Upon reaching ignition temperature (which takes place rapidly) the material combusts and transfers heat back into the bed. Continued bed agitation by the fluidizing air allows larger waste particles to remain suspended until combustion is completed. Residual fines (ash) are carried off the bed by the exhausting flue gases at the top of the combustor. These gases are subsequently processed and/or scrubbed before atmospheric discharge.

Process Design. In specifying or designing a fluidized bed combustor, primary factors to be considered are: gas velocity; bed diameter; bed temperature; and, the type and composition of waste to be incinerated.

Gas velocities are typically low, in the order of 5 to 7 ft/sec. Maximum gas velocity is constrained by the terminal velocity of the bed particles and is therefore a function of particle size. Higher velocities result in bed attrition and an increased particulate load on downstream air correction equipment. Relatively low velocity reduces pressure drop and therefore lowers power requirements.

Present fluidized bed design technology limits the bed diameter to 50 ft or less. At nominal values of gas velocity and temperature, the maximum volumetric flow would be approximately 2.5X10^6 acfm.

Bed depths range from about 15 inches to several feet. Variations in bed depth affect waste particle residence time and system pressure drop. One therefore desires to minimize bed depth consistant with complete combustion and minimum excess air.

Bed temperatures are restricted by the softening point of the bed material. If sand is used, temperatures should be maintained below 2000 F to avoid softening and consequent agglomeration of the particles.

The type and composition of the waste is a significant design parameter in that it will impact storage, processing and transport operations (prior to incineration), as well as the combustion. If the waste is a hetrogeneous mixture such as municipal refuse and has a relatively low (<8,000 Btu/lb) heating value, processing (shredding, sorting, drying, etc.) operations will be more complex and auxiliary fuel addition to the combustor will be required. Homogeneous wastes which can be injected and uniformly dispersed in the bed should facilitate overall system design and minimize the bed volume.

Process Economics. Installation and operating costs will vary significantly depending upon the type of waste to be processed and the quantity and sophistication of water and air correction equipment required. Lund[0285] indicates that investment costs and operating costs are approximately $20 and $5 per ton respectively.

Process Modifications. The fluidized bed combustor will noramlly be incorporated in an overall material handling, processing and disposal system to simultaneously cope with solid, liquid and gaseous waste or by-products. This is illustrated schematically in a block diagram (Figure 5) which has the following elements:

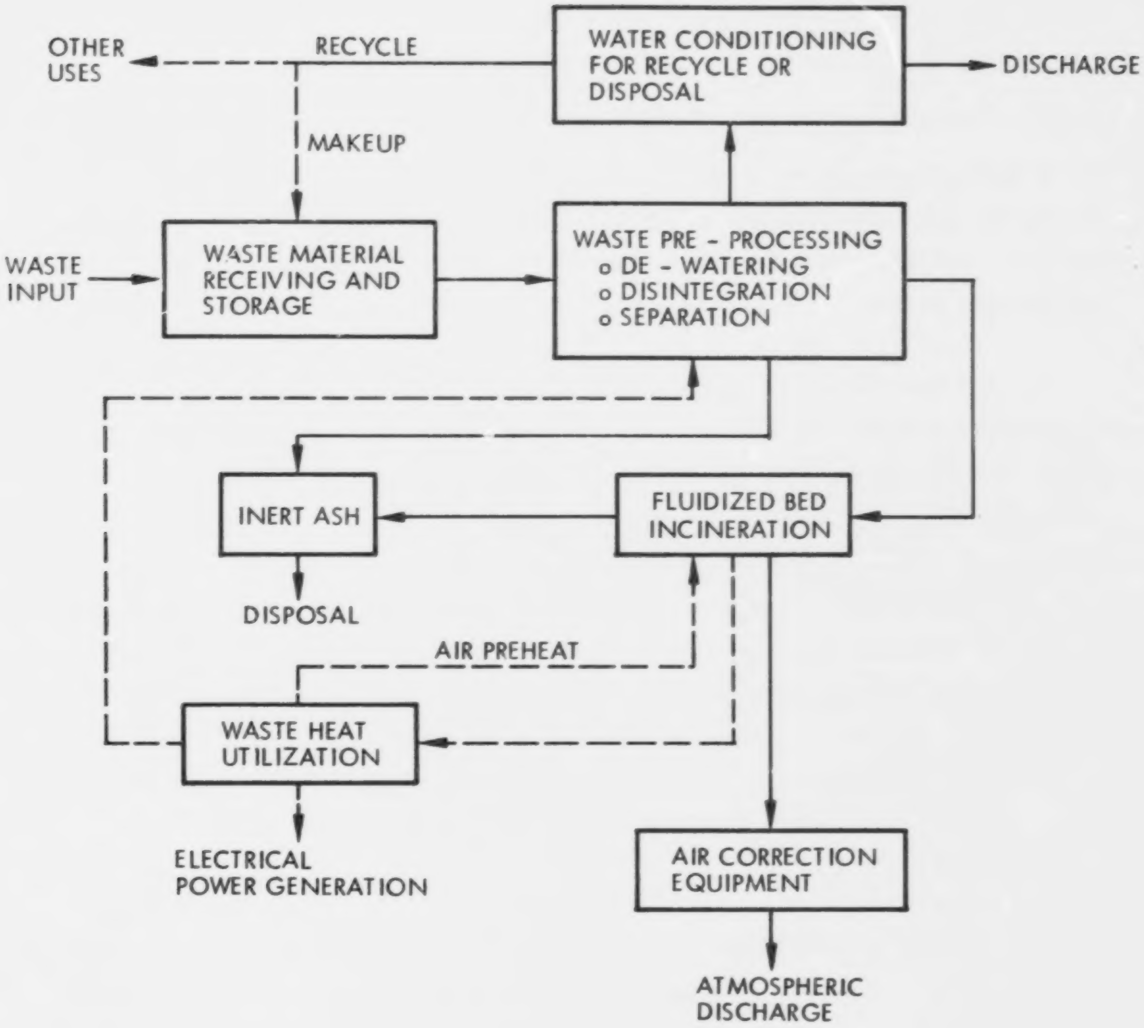
OTHER USES
RECYCLE
WATER CONDITIONING FOR RECYCLE OR DISPOSAL
DISCHARGE
MAKEUP
WASTE INPUT
WASTE MATERIAL RECEIVING AND STORAGE
WASTE PRE - PROCESSING
o DE - WATERING
o DISINTEGRATION
o SEPARATION
INERT ASH
FLUIDIZED BED INCINERATION
DISPOSAL
AIR PREHEAT
WASTE HEAT UTILIZATION
ELECTRICAL POWER GENERATION
AIR CORRECTION EQUIPMENT
ATMOSPHERIC DISCHARGE

Figure 5. Functional Diagram for Fluidized Bed Incineration Disposal of Combustible Waste Material

(1) Receipt and storage of waste materials.

(2) Processing or conditioning waste materials prior to incineration.

(3) Waste material transport and handling.

(4) Waste incineration.

(5) Air correction of off gases from combustion.

(6) Disposal and/or recovery of residual solid and liquid by-products.

Incineration systems incorporating fluidized bed combustors vary depending upon the application and economic desire to utilize waste heat. Usually, systems will incorporate most if not all of the functional activities illustrated (Figure 5).

Most of the fluidized bed incineration application reported in the literature involve the disposal of sludges or slurried wastes. This may necessitate a dewatering step in processing the waste prior to incineration if combustion gases are to be used for steam-electric or gas turbine power generation. If power generation is a desired by-product of the incineration process, then waste moisture content values less than approximately 60 percent are required.[1574] Moisture values in excess of this value, or heavy concentrations of inert matter will require auxiliary fuel burners to preheat the waste and ensure sufficient heat content in the flue gases. Pre-drying of the sludge may be accomplished by aeration or more sophisticated mechanical systems involving the addition of heat.

Waste material is pneumatically, mechanically or gravity fed into the fluidized bed. Normally, inhomogeneous waste material must be reduced in size (shredded, pulverized, etc.) to facilitate the feed system operation and permit injection, distribution and combustion within the fluidized bed.

In addition to reducing moisture content and waste material size, separation of non-combustible material such as ferrous and non-ferrous metals may be required. The former may be removed using magnetic separators. Non-ferrous metals are commonly removed using ballistic-type separators.

The tasks of receiving, storing, processing and transport of more hazardous wastes may often require a completely closed system. In this case, aeration in the conventional manner will be unacceptable. Enclosed hot air dryers using recycled combustion gases may be considered; however, the addition of gas or oil fuel burners to the incinerator (to accomplish waste drying) will probably result in higher initial equipment costs. An auxiliary burner system will be required in any event for startup and bed temperature conditioning.

Combustion of any waste which results in particulate, odors or gaseous stack emissions (other than water vapor and CO_2) may require air correction equipment to meet emission standards. Particulate emissions may be controlled using one or more of the following general categories of collectors; dry collectors, wet scrubbers, electrostatic precipitators and fabric filters.

Auxiliary air correction equipment for odor control should not be required with the fluidized bed incinerator process. In this instance, odors will be eliminated by oxidation in the combustor. The operating temperature of the fluidized bed combustor is 1400 to 1500 F which is adequate for most odor producing compounds.[0285] If odor control is a problem with certain hazardous wastes, then an afterburner can be added to the incineration process as a means of control.

Control of gaseous pollutants will depend upon the waste and its combustion products. Because of its relatively low and controlled temperature environment, fluidized bed incinerators should produce little or no nitric oxide, a distinct advantage for this type of equipment.

A rather interesting and unique technique for scrubbing sulfur oxides with fluidized beds is the utilization of calcined limestone particles in place of sand as the bed material.[1575,1576] Scrubbing efficiencies up to 90 percent have been obtained in experimental applications involving fossil fuel combustion gases.[1575] In this work, the fluidized bed was utilized purely as a desulfurization device, and not as a combustor. However, it is conceivable that a limestone bed or a sand-limestone mixture could be used in place of pure sand in an incinerator application to scrub a significant portion of the sulfur oxides produced by the waste combustion. The remaining sulfur oxides would be removed by conventional wet scrubbing equipment. It should again be emphasized that this is a conceptual approach and has not been reduced to practice.

Process Applicability. The fluidized bed incinerator is generally applicable to the ultimate disposal of combustible solid, liquid and gaseous wastes; a significant advantage over most other incineration methods. For that reason, it is probable that this type of incineration unit would find application at a National Disposal Site, especially considering its suitability to the disposal of sludges generated in any biological treatment facilities which would be present at the site. It has the following advantages and limitations:

Advantages

(1) The combustor design concept is simple and does not require moving parts in the elevated temperature regions of combustion.

(2) Designs are compact due to high volumetric heating rates (100,000 to 200,000 Btu/hr-ft^3) resulting in lower capital investment.

(3) Comparatively low gas temperatures and excess air requirements* minimize formation of nitric oxide.

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*For example, excess air requirements as low as 5 percent have been reported in the combustion of coal in fluidized bed reactions. Low excess air requirements reduce the size and cost of gas handling equipment.

Limitations

(1) Bed diameters are limited with present design technology; therefore, maximum volumetric flow rates per unit are limited.

(2) Removal of inert residual material from the bed is a potential problem area.

Catalytic Incineration

Catalytic incinerators are devices which are used to dispose of low concentration combustible materials in the gaseous state. Catalytic incineration, or as it is more commonly called, catalytic combustion or catalytic oxidation, has been successfully used in the chemical process industries for incineration of paint solvents, odors from chemical manufacture and food processing and many other functions that help offset the cost of air pollution control equipment.[1533]

Operating Principle. There are five steps in any solid catalyzed vapor phase reaction.[0304] These five basic steps are:

(1) Diffusion of the reactants through the stagnant fluid around the surface of the catalyst.

(2) Adsorption of the reactants on the catalytic surface.

(3) Reaction of the adsorbed reactants to form products.

(4) Desorption of the products from the catalytic surface.

(5) Diffusion of the products through the pores and surface film to the bulk vapor phase outside the catalyst.

Therefore, given the identical support, the rate of steps (1) and (5) would be approximately equal regardless of the dispersed catalytic metal which is present. The criteria which govern the effectiveness of operation for various catalytic metals must therefore fall into steps (2), (3) or (4). These criteria include reaction temperature, waste material concentration, excess oxygen available, the chemical composition of the catalyst and the geometric configuration of the individual catalysts.

The operating efficiency (percent of the waste organic combusted to carbon dioxide and water) of a catalytic system is strongly dependent upon the catalyst temperature. Increased catalyst temperatures generally result in increased removal efficiencies. A tabulation of removal efficiencies of various solvents as a function of catalyst temperature is presented (Table 6).[0862] The data summarizes the type and quantity of coating applied, the type and quantity of solvent evolved, the oven temperature, the catalyst temperature and the removal efficiency for a coating oven during tests with a catalytic incinerator.

The waste compound concentration as well as the oxygen concentration in the gas stream have marked effects upon catalytic combustion efficiency. The combustible waste concentration in the gas stream have marked effects upon catalytic combustion efficiency. The combustible waste concentration

TABLE 6

CATALYTIC OXIDATION OF SOLVENT VAPORS EVOLVED FROM A COATING OVEN*[0862]

Coating Type	Quantity of Coating gal/hr.	Evolved Solvent	Solvent Quantity Envolved lb/hr.	Average Oven Temp. F	Catalyst Temp. F	% Solvent Removal
Vinyl	19	Xylol and Isophorone	120	350	800	28
					920	54
					1050	77
					1200	93
Vinyl	43	Methyl/isobutyl Ketone	271	340	840	77
					890	79
					930	85
					990	88
Epoxy	18.6	Xylol and Butyl Cellosolve	86	350	800	79
					900	81
Phenolic	18.5	Mineral Spirits	88	414	730	65
Oleoresinous	17.5	Mineral Spirits	77	425	800	80
					920	89
					1050	94
					1200	95
Alkyd	8	Mineral Spirits	30	290	690	41
					700	52
					800	80
					920	89
					1050	94
					1200	95

* The catalysts discharge temperature was held constant for each test and superficial gas velocities were constant within ± 15 percent for all data points.

in the stream to be treated should never exceed the lower flammability limit in order to guard against explosion and fire. However, it is desirable to operate with as high a concentration of combustible (below the lower flammability limit) as possible since conversion efficiencies are generally proportional to combustible compound concentrations when other operating variables are held constant. The conversion efficiency of catalytic combustors is also effected by the oxygen concentration present in the feed gas stream. It has been found that increased oxygen concentration results in increased efficiency when other parameters are held constant. There is, however, a trade-off, as oxygen concentration is increased in a gas stream (through air injection), the contaminant concentration is decreased. That is, the efficiency of the system will be increased by oxygen addition while simultaneously being decreased by contaminant dilution. There is generally an optimum which must be determined for individual disposal systems. The normal effective range for catalytic oxidation extends from a very few parts per million of combustible up to a heating value of 20 Btu/std cu ft.[0304]

The chemical composition of a catalyst affects conversion efficiencies. The various noble metals such as platinum, palladium, rhodium, etc., as well as copper chromite and the oxides of copper, chromimum, manganese, nickel, and cobalt, in varying concentrations have been applied successfully to the catalytic oxidation of various combustible compounds. However, in air pollution control it has not been practical to undertake research programs to develop specific catalysts for each problem. Therefore, the goal of commercial manufacturers has been to make available universal catalysts which are effective in oxidizing the entire range of organic materials over an extended period of exposure time with minimum maintenance and replacement.[0304,0862]

When selecting a catalyst material care must be taken to make sure that there are no poisoning agents, activity suppressants or fouling agents present which inhibit the catalysts' effectiveness. With platinum family catalysts, contaminants to look out for are:

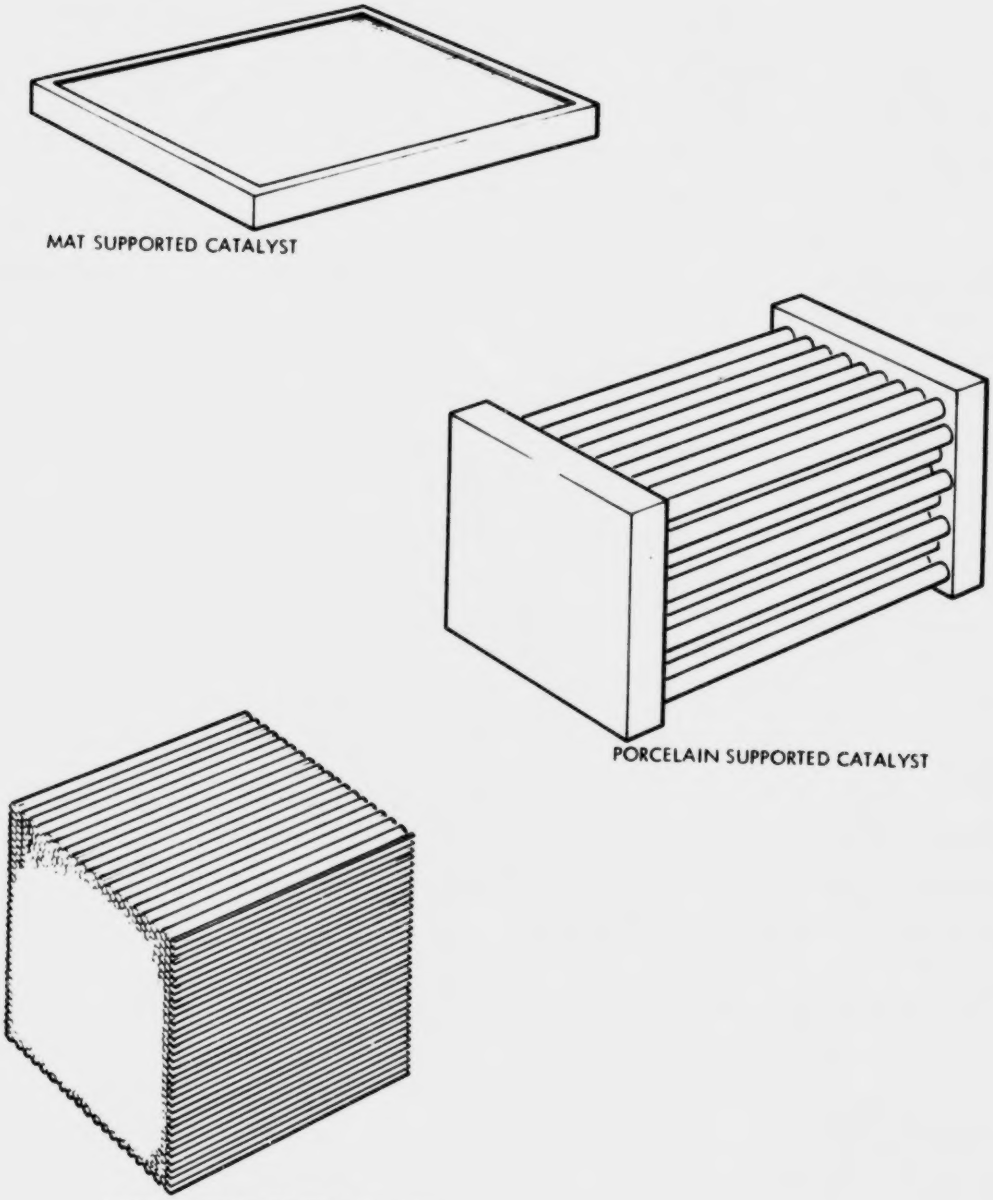
Poisons: Heavy metals
Phosphates
Arsenic compounds

Suppressants: Halogens (elemental and compounds)
Sulfur compounds

Fouling Agents: Alumina and silica dusts
Iron oxides
Silicones

Other materials that may reduce catalytic effectiveness in general are the vapors of metals such as mercury, zinc and lead.[0862,1533] Catalyst manufacturers can generally specify which materials are detrimental to catalysts which they market.

The geometric configuration of the individual catalysts can also influence the extent of the oxidation of a gaseous waste. There are many commercial catalysts available in pellet, spherical or ring form. However, in air pollution work, which is generally operated at or near atmospheric pressure, usually the pressure drop through catalyst beds of these types is so large that the horsepower of the waste gas fan becomes too great for economical operation. Therefore, three general commercial catalysts with a very low pressure drop (1/4 to 1/2 in.W.C.) have been developed (Figure 6). The first is a mat type catalyst similar to an air filter. It consists of a ribbion type "Nichrome" or stainless steel wire to which the catalytic material has been applied, randomly packed between screens and mounted in a stainless steel frame. The second is a porcelain assembly consisting of two end plates which are secured by a center post and a number of teardrop-shaped rods to which the catalyst is applied. In this case the carrier is procelain which is first coated with activated alumina and then with an active metal coating. The third is honeycomb type ceramic material to which the catalytic material is applied.[0304] The geometric configuration best suited for specific applications can usually be suggested by the catalyst manufacturer.



MAT SUPPORTED CATALYST

PORCELAIN SUPPORTED CATALYST

HONEYCOMB SUPPORTED CATALYST

Figure 6. Commercially Used Catalyst Configurations[0304]

Process Design. There are certain prerequisites required for an efficient catalytic operation. The basic requirements include intimate mixing of the combustibles in the stream to be treated. The stream must be brought up to the catalytic ignition temperature for the combustible to be burned, and good temperature distribution through the catalyst bed is essential. Sufficient oxygen must be present in the waste effluent or must be added to it to ensure oxidation of the materials. The system must be designed so that proper velocities and retention times through and within the catalyst bed are maintained.

The influent gas stream should be free of particulate in order to ensure against catalyst fouling. Therefore, if the stream contains high particulate loadings, a pretreatment of filtration or electrostatic precipitation would be required prior to catalytic oxidation. In such cases, it is generally more economical to treat the waste gas stream with thermal incineration.

Basically, a catalytic incinerator consists of an afterburner housing containing a preheating section (if one is necessary) and a catalyst section. A gas burner preheats the contaminated gases before they flow to the catalyst section. Drawings of two catalytic incinerator installations are presented (Figures 7 and 8). An arrangement for the recovery of heat from the incinerator gases is illustrated (Figure 8).

Frequently, the contaminated gases are delivered to the afterburner by the fan exhausting process equipment. In one type of catalytic incinerator, the exhaust fan is located within the afterburner housing between the preheat burner and the catalyst bed. This fan also mixes the gases and distributes them evenly over the catalyst. Condensates do not occur in the fan since it operates above condensation temperature. Of course, the fan must be constructed of materials that can withstand the maximum temperature of the gases being handled.

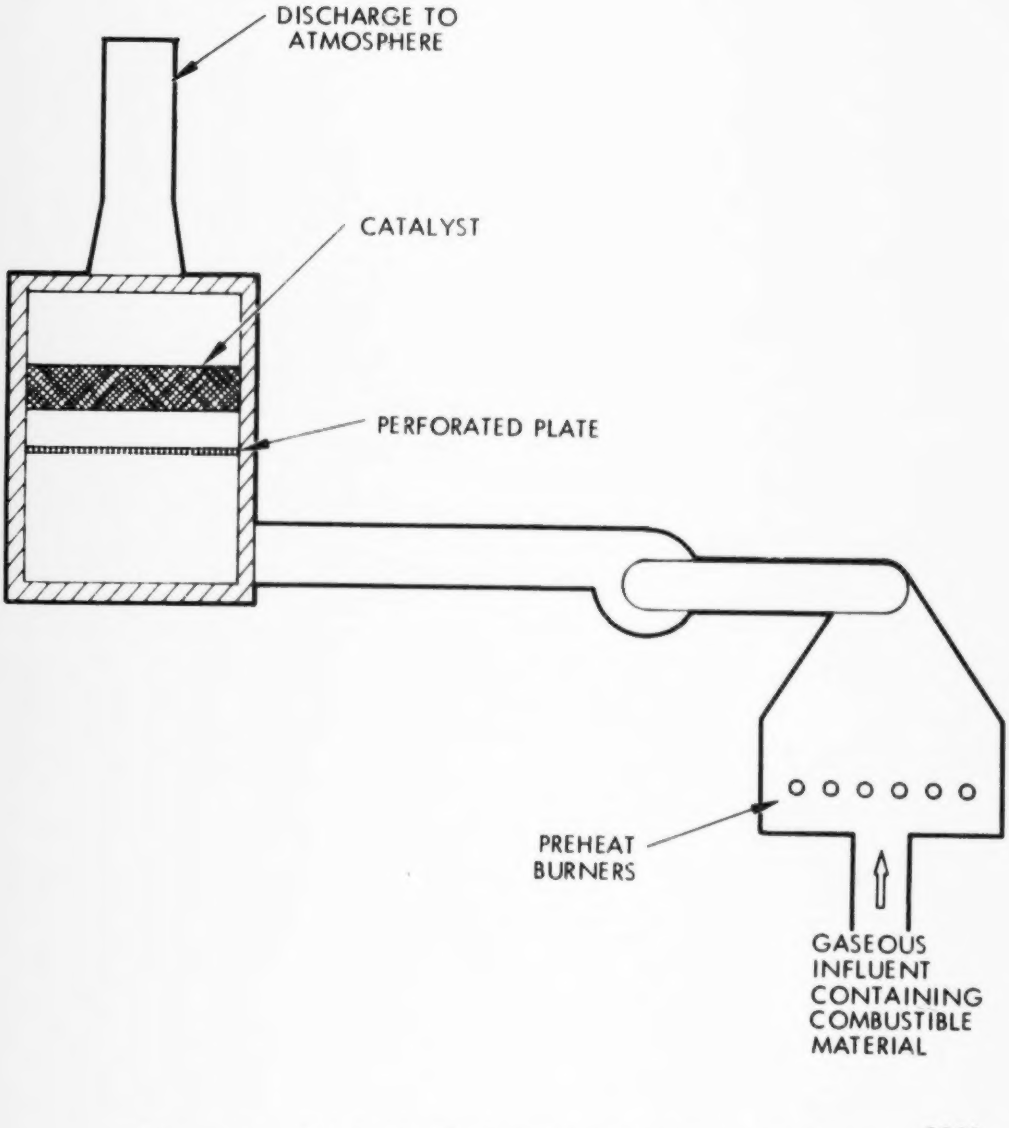

DISCHARGE TO ATMOSPHERE
CATALYST
PERFORATED PLATE
PREHEAT BURNERS
GASEOUS INFLUENT CONTAINING COMBUSTIBLE MATERIAL

Figure 7. Catalytic Incineration Without Heat Recovery[0862]

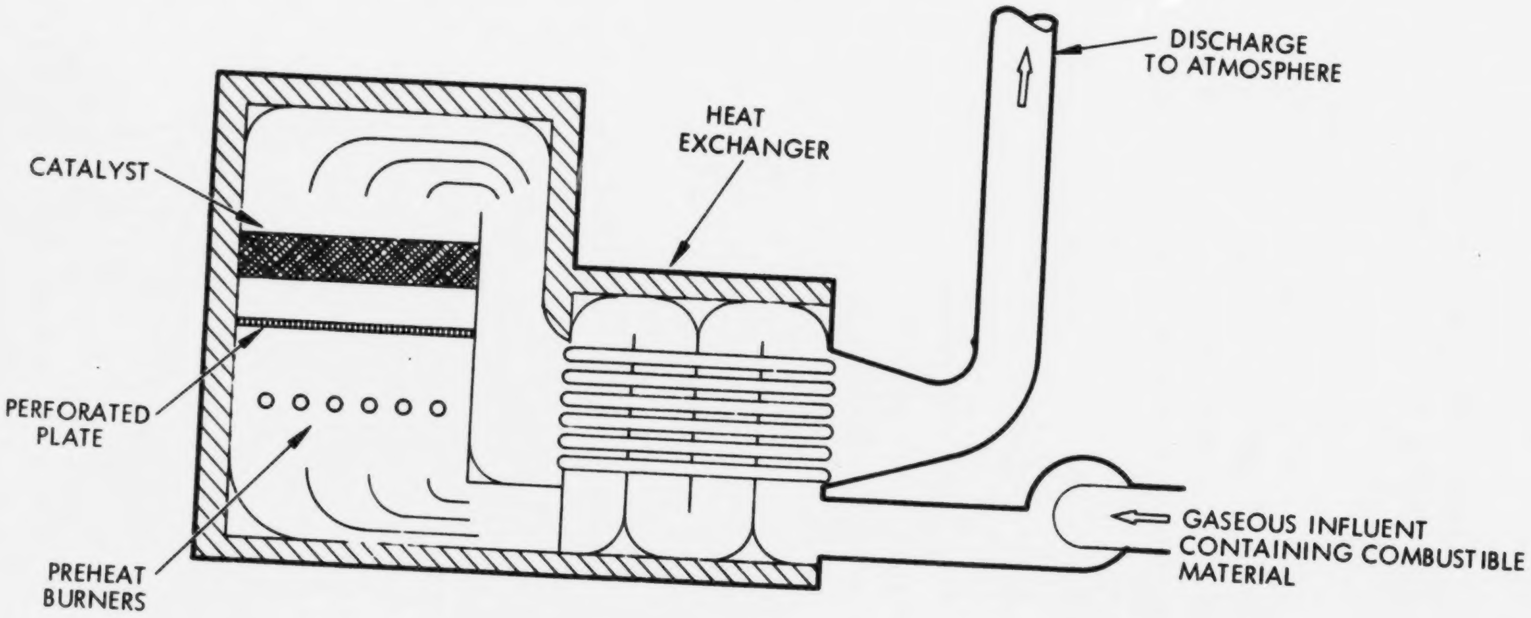

CATALYST
PERFORATED PLATE
PREHEAT BURNERS
HEAT EXCHANGER
DISCHARGE TO ATMOSPHERE
GASEOUS INFLUENT CONTAINING COMBUSTIBLE MATERIAL

Figure 8. Catalytic Incineration with Heat Recovery[0862]

The interior chamber of the afterburner may be constructed of 11 to 16 gage black iron, heat-resisting steel, stainless steel, or refractory materials. Heat-resisting steel should be used for operating temperatures between 750 and 1,100 F; stainless steel is recommended for operating temperatures exceeding 1,100 F. Refractory materials are recommended for temperatures exceeding 1,300 F. A thickness of 4 to 6 inches of similar thermal insulation is required unless refractory materials are used. The exterior sheet is usually fabricated from 16 to 20 gage mild steel. The framework is usually fabricated from standard structural steel. Gas velocities through the chamber of about 20 fps have been found satisfactory.[0862]

The contaminated gases are preheated to the reaction temperature by a gas burner before passing thorugh the catalyst. When the preheat burner is on the discharge side of a fan, a premix gas burner is normally used because of the positive pressure in the combustion chamber. When the fan is between the preheat burner and the catalyst bed, an atmospheric burner may be used since a negative pressure exists in the preheat section of the combustor. Sizing the preheat burner to increase the temperatue of the contaminated gases to the required catalyst discharge temperature without regard to the heating value of the combustible materials is advisable especially if considerable variation in concentration occurs. The concentration of combustibles from process equipment is normally 25 percent of the lower explosive limit or less to meet the requirements of the National Board of Fire Underwriters. Experience indicates that the preheat burner should have sufficient capacity to heat the contaminated gas stream to 950 F minimum to obtain adequate catalytic combustion of the compounds that are more difficult to burn.[0862] some burning of contaminants usually occurs in the preheating zone. The preheated gases then flow through the catalyst bed where the remaining combustible contaminants are burned by catalysis.

A direct relationship is believed to exist between the autoignition temperature of an organic vapor and the temperature at which catalytic oxidation will occur. In other words, the higher the autoignition temperature of a compound, the higher the expected temperature required for catalytic oxidation.[0862]

Catalytic incinerators possess an inherent maintenance factor not present in other types of incinerators; namely, that usage of the catalyst produces a gradual loss of activity through fouling and erosion of the catalyst surface. Occasional cleaning and eventual replacement of the catalyst are therefore required.

Modulating controls on the burner regulated by the catalyst discharge gas temperature are usually used. This allows the fuel gas input to the preheat burner to be reduced as the rate of heat released in the catalyst bed increases as a result of larger concentrations of combustible vapors. The sensing instrument commonly used is a type employing a fluid-filled bulb for detecting gas temperature with capillary and bellows. Movement of the bellows is amplified and transmitted to the preheat burner gas valve and combustion air blower blast gate. Electronic instruments are used less frequently because of considerably greater cost.[0862]

When operating conditions do not vary greatly, an improved means of ensuring maximum combustion efficiency seems to be the firing of the preheat burner at a fixed input capable of heating the contaminated gases to the temperature required for complete oxidation at the maximum rate of influx. Installation of a high-temperature-limiting control on the downstream side of the catalyst may be necessary to prevent overheating of the catalyst section.[0862]

Finally, the burned gases are discharged through a stack to the atmosphere, to a process that may use the sensible heat of the exhaust gases, such as a bake oven or dryoff oven, or they may be passed through an exchanger for heating the gases entering the combustor, which thereby reduces the amount of fuel required by the preheat burners.

Process Economics. The installed capital investment cost of a catalytic incineration system is a function of the difficulty of the combustion reaction, inclusion of auxiliary equipment, materials of construction and the extent of heat recovery. Operating costs generally reflect fuel consumption in the preheater (and are therefore a function of influent gas temperature, catalyst temperature, and heat recovery) as well as periodic catalyst replacement of activation. Estimates from various literature sources of both capital and operating costs are presented (Table 7).

Process Modifications. Basically, the only process modifications utilized in catalytic incineration is waste heat recovery through heat exchange with or recirculation of the hot effluent gas exiting the catalyst bed. Where the combustible concentration is relatively high, i.e., where the temperature rise through the bed approaches 400 F or more, it is often desirable to take a portion of the hot gases after passage through the catalyst and recirculate them, combining them with relatively low temperature influent prior to introducing them into the catalytic system. In this way, a stream at approximately 300 F could be combined with a portion of the effluent from the catalyst at 700 F, bringing the inlet temperature up to 500 F, thereby reducing the preheat to a minimum. Another method of reducing the preheat required, even when the combustible content is relatively low, is to incorporate a heat exchanger. The influent to the process is passed through the "cold" side of the heat exchanger, then passed over the preheat burner and through the catalyst bed. The effluent from the catalyst is passed through the "hot" side of the heat exchanger, thereby increasing the temperature of the influent up to the approximate ignition temperature of the catalyst. These two alternatives along with that of not utilizing heat recovery are presented (Figure 9).[0304]

TABLE 7

PROCESS ECONOMICS FOR CATALYTIC INCINERATION

	Amount of Gas Treated scfm[a]	Influent Gas Temp. F	Capital Cost $/scfm	Annual Fuel Cost $/Year
Data from Reference No. 1533				
Basic Catalytic Unit	10,000	350	2.30	14,600
		550	2.30	4,800
Catalytic Unit with Heat Exchanger	10,000	350	2.85	7,100
		550	3.39	(c)
Data from Reference No. 0285				
Basic Catalytic Unit	10,000	300	2.00 - 2.50	(b)
Catalytic Unit With Heat Exchanger	10,000	300	3.50 - 4.50	(b)
Data From Reference No. 1461				
Basic Catalytic Unit	5,000	400	3.00	3,800

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[a] Contaminants are at less than 25% of L.E.L.

[b] No data available

[c] No fuel is required. The preheat exchanger saves $14,600 annually in fuel costs.

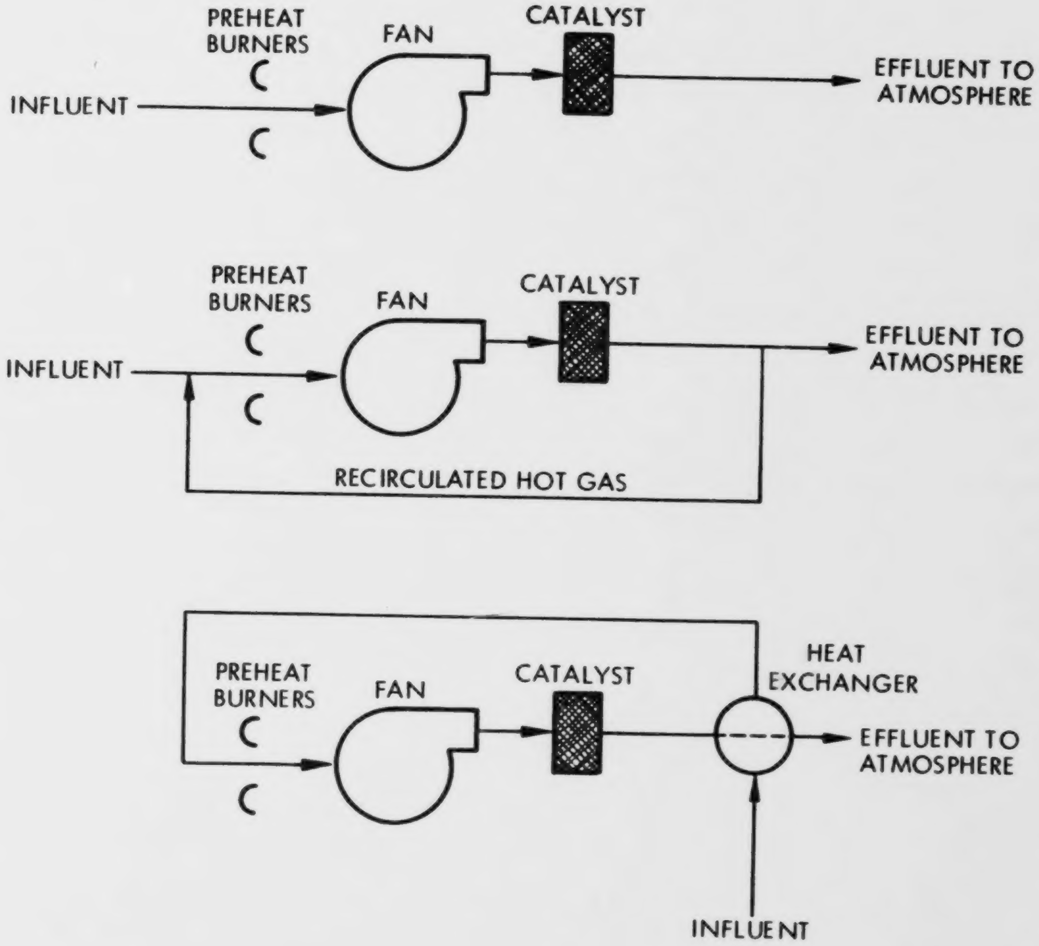

PREHEAT BURNERS
FAN
CATALYST
INFLUENT
EFFLUENT TO ATMOSPHERE
PREHEAT BURNERS
FAN
CATALYST
INFLUENT
EFFLUENT TO ATMOSPHERE
RECIRCULATED HOT GAS
PREHEAT BURNERS
FAN
CATALYST
HEAT EXCHANGER
EFFLUENT TO ATMOSPHERE
INFLUENT

Figure 9. Heat Recovery Options[0304]

Process Applicability. Due to the form of the waste material to be treated (dilute and in the gaseous state) catalytic incineration is best suited for use at the processing site where the waste material is generated. A listing of some of the typical industrial applications of catalytic incineration systems is presented (Table 8).

Catalytic incineration would find use at a National Disposal Site only as a secondary treatment (i.e., afterburner) on primary treatment processes evolving varying amounts of miscellaneous hydrocarbons, alcohols, amines, acids, esters, aldehydes and many other contaminants which are basically hydrocarbon in nature. These materials have varying degrees of toxicity and different odor levels; however, they all lend themselves to catalytic oxidation. Generally, the commercial catalysts available for installation in operations which emit compounds of this kind are not specific. That is, they tend to oxidize all combustible organic compounds in the stream regardless of their type and concentration. Catalysts are also effective in the reduction of oxides of nitrogen and in burning sulfur bearing compounds such as hydrogen sulfide and carbon bisulfide.[0304]

TABLE 8

TYPICAL INDUSTRIAL APPLICATIONS OF CATALYTIC INCINERATION SYSTEMS[1580]

Automotive paint baking
Coil & strip coating
Metal parts finishing
Metal decorating
Wire enameling
Hardboard coating & curing
Resin manufacture
Oil bodying
Varnish cooking
Oil sulfurization
Acrylate polymerization
Oil hydrogenation
Oil quenching
Asphalt blowing
Tar & asphalt coating & saturating
Phthalic and maleic anhydride manufacture
Nitric acid plants
Etching & dissolving metals with nitric acid
Fungicide manufacture
Pharmaceutical manufacture
Vitamin manufacturing
Rice browning
Corn popping
Nut roasting
Coffee roasting
Smoke houses
Potato chip cooking
Rendering of animal by-products
Carbon baking
Metal chip drying
Foundry core baking
Brake shoe bonding and burn-off
Paper coating
Printing
Fabric finishing & curing
Paper mill digesters
Fertilizer processing
Waste water stripping incinerators
Investment casting & mold burnout
Synthetic rubber manufacture
Sewage treatment

Rotary Kiln Incinerators

Rotary kiln incinerators are versatile units which can be used to dispose of solid, liquid and gaseous combustible wastes. They have been utilized in both industrial and municipal installations.[0167,1002,1672,0053] In addition, applications of rotary kiln incineration to the disposal of obsolete chemical warfare agents and munitions have been reported.[0958,1688,1689]

Operation Principle. The rotary kiln incinerator is a cylindrical shell lined with firebrick or other refractory and mounted with its axis at a slight slope from the horizontal. It is a highly efficient unit when applied to solids, liquids, sludges and tars because of its ability to attain excellent mixing of unburned waste and oxygen as it revolves. Its use as a concentrated waste gas combustor is considered a secondary application. This is due to the fact that although proper conditions are present for efficient gas combustion (i.e., long residence time at elevated temperatures) there is no need for the cylinder to be rotating. Therefore rotary kiln incinerators are used for gaseous waste combustion only in conjunction with solid or liquid waste incineration.

Rotary kiln incinerators used in municipal applications are generally designed to handle large volumes of solid combustible waste (refuse) along with any entrained liquid. In this type of facility, the kiln actually serves as a secondary combustion unit since the waste material is ignited on traveling grates prior to entering the kiln (Figure 10). In this instance, the kiln serves mainly as an efficient mixer of the burning waste with combustion air.[0053]

Rotary kiln incinerators when applied to industrial (includes military) applications are generally designed to accept both solid and liquid feed. A typical major industrial installation is operated by the Dow Chemical Company at Midland, Michigan (Figure 11)[1002]. This particular unit consists of a 65 million Btu/hr kiln that is used for the incineration of solid chemical refuse, liquid residues, paper, wood and other solids of varying Btu/content. A pack-feed mechanism is used to feed packs and drums of solid waste chemicals into the incinerator.

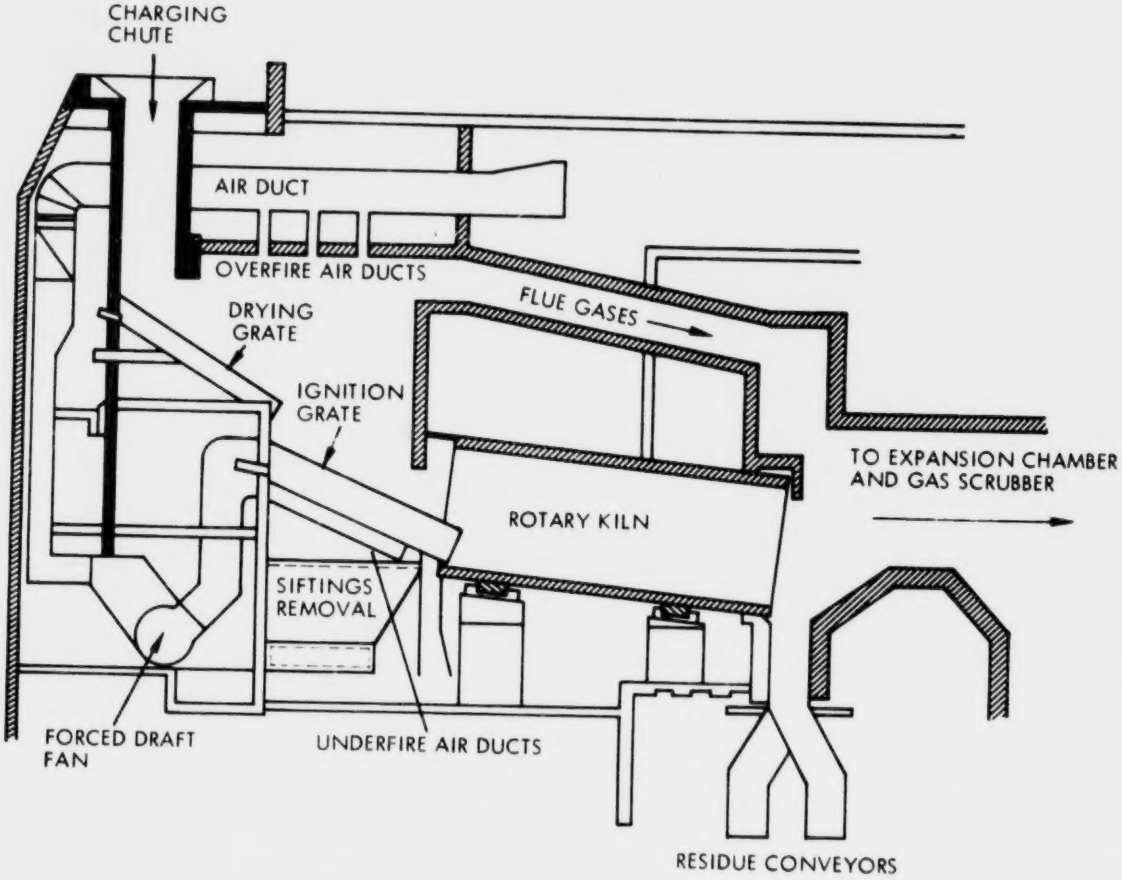

CHARGING CHUTE
AIR DUCT
OVERFIRE AIR DUCTS
DRYING GRATE
IGNITION GRATE
FLUE GASES
ROTARY KILN
TO EXPANSION CHAMBER AND GAS SCRUBBER
SIFTINGS REMOVAL
FORCED DRAFT FAN
UNDERFIRE AIR DUCTS
RESIDUE CONVEYORS

Figure 10. Municipal Rotary Kiln Incineration Facility[0053]

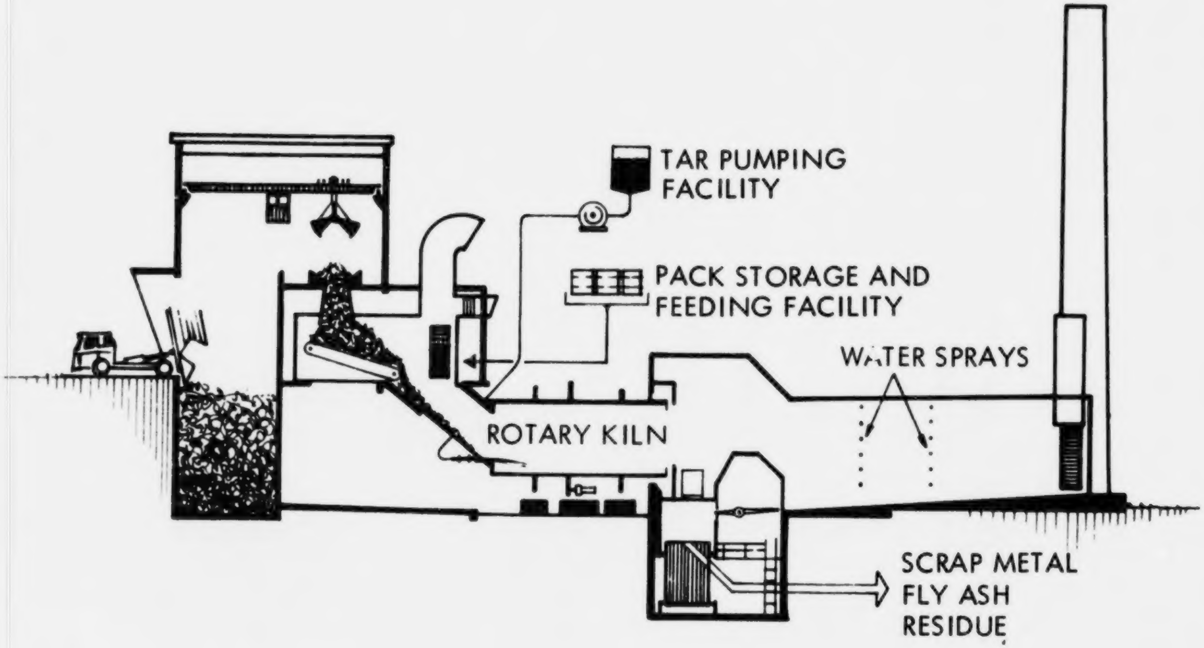

TAR PUMPING FACILITY
PACK STORAGE AND FEEDING FACILITY
WATER SPRAYS
ROTARY KILN
SCRAP METAL
FLY ASH
RESIDUE

Figure 11. Typical Major Industrial Rotary Kiln Incineration Facility[1002]

Liquid wastes transported to the incinerator are transferred to designated receiving tanks that contain compatible wastes. All drums of liquid wastes are also transferred to the receiving tank by the way of a drum-dumping dock. The waste is strained as it is pumped from the receiving tank into a burning tank, where it is blended for optimum burning characteristics. All liquid residues are burned in suspension by atomization with steam or air.

Drum quantities of solid tars are destroyed by feeding them into the rotary-kiln incinerator via a hydraulically operated drum and pack-feeding mechanism. All refuse, except full drums and packs of material, is dumped into the refuse pit. An overhead crane is used to mix the refuse and raise it to the charging hopper of the rotary kiln (see Figure 11).

While the solid refuse is being fed, liquid tars are fired horizontally into the rotary kiln. As the refuse moves down the kiln, organic matter is destroyed, leaving an inorganic ash. This ash [illegible] made up primarily of slag, and other nonburnables such as drums and other metallic material. The ash discharges from the end of the kiln into a conveyor trough that contains water. Afer quenching, the material is conveyed into a dumping trailer, and then to a landfill.

After leaving the kiln, the products of combustion enter the secondary combustion chamber and impinge on refractory surfaces that cause a swirling action. No secondary fuel or afterburners are used. Downstream of the secondary combustion chamber, the gases pass through several banks of water sprays in which the flyash is knocked down and sluiced onto the ash-conveyor floor. Cooled gases pass under a stack damper and then to a 200-ft. stack.

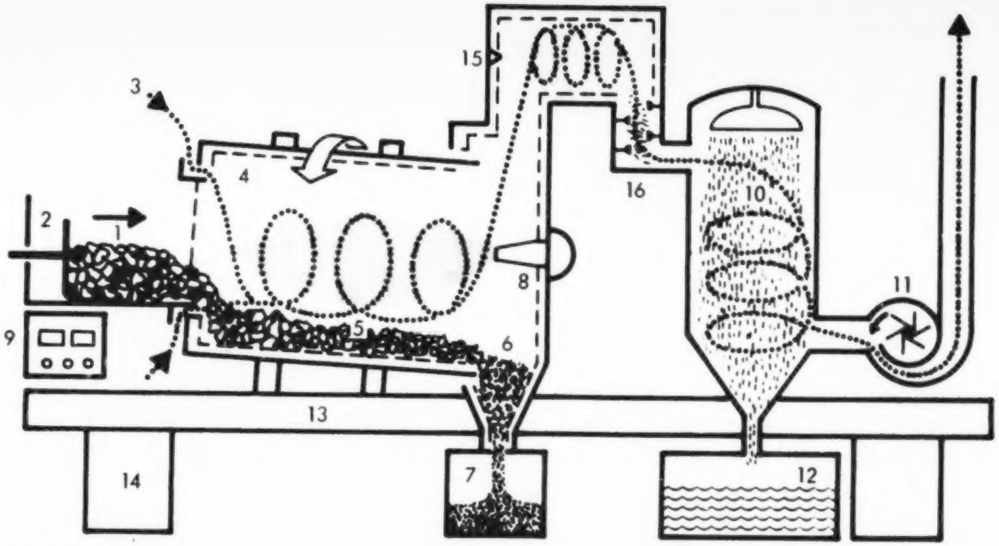
There are a variety of small relatively portable and inexpensive rotary kiln incinerators currently marketed. These units usually are not as versatile as large installations because they generally lack the auxiliary equipment utilized in pretreatment of heterogeneous feeds.

An example of this type of unit is the completely packaged compact THUMBLE-BURNER, designed by Bartlett-Snow (Figure 12).[1672] These units have capacity ranging from 100 pounds to 2 tons per hour with corresponding overall system dimensions ranging from 5X5X15 feet to 14X15X34 feet. This type of system will efficiently incinerate properly sized solid waste material with heat content ranging from 1000 to 15,000 Btu per pound. It is also capable of burning gaseous and liquid wastes when they are injected through the auxiliary burner which is used for incinerator temperature control.

The rotary kiln has been successfully applied to the incineration of obsolete or excess chemical warfare agents (GB, VX and mustard)[0958]. In this case, the waste is carefully fed to the unit at a relatively slow flow rate and supplemented by fuel oil flame. The liquid chemical warfare agents are fed cocurrent to the fuel oil flame. All incineration controls are fail-safe and the agent feed is equipped with a fast acting cutoff valve in the event of loss of flame.

The combustion gases leaving the incinerator are water quenched before being processed through a cross-flow packed scrubber to remove objectionable constituents of the combustion products. The scrubbing media are $Ca(OH)_2$ and NaOH for both GB and mustard and HNO_3, NaOH and $Ca(OH)_2$ for VX incineration products. In all cases, the products recovered and dried by the pollution control system are calcium salts. These solids must then be sent to ultimate disposal.[0958]

Rotary kilns have also been used to incinerate explosives such as obsolete munitions. In this case, the explosive is fed countercurrent to a fuel oil flame. The kiln is equipped with an internal spiral to convey materials through the furnace. Feed and discharge is accomplished with metal conveyers. The effluent fume scrubbing system consists of a packed bed scrubber, utilizing a sodium carbonate solution, followed by a hydroclone or venturi scrubber. The scrubber liquor containing fly ash and a sodium nitrate-nitrite mixture is then dried and sent to ultimate disposal.[0958,1688]



1 WASTE TO INCINERATOR
2 AUTO-CYCLE FEEDING SYSTEM:
FEED HOPPER, PNEUMATIC FEEDER, SLIDE GATES
3 COMBUSTION AIR IN
4 REFRACTORY-LINED, ROTATING CYLINDER
5 TUMBLE-BURNING ACTION
6 INCOMBUSTIBLE ASH
7 ASH BIN
8 AUTO-CONTROL PACKAGE:
PROGRAMMED PILOT BURNER
9 SELF-COMPENSATING INSTRUMENTATION-CONTROLS
10 WET-SCRUBBER PACKAGE:
STAINLESS STEEL, CORROSION-FREE WET SCRUBBER; GAS QUENCH
11 EXHAUST FAN AND STACK
12 RECYCLE WATER, FLY-ASH SLUDGE COLLECTOR
13 SUPPORT FRAME
14 SUPPORT PIERS
15 AFTERBURNER CHAMBER
16 PRECOOLER

Figure 12. Portable Rotary Kiln Incineration Units[1672]

Process Design. Specific data on rotary kiln incinerator design parameters are scarce. This is due to the fact that incineration is a relatively new application for rotary kilns. Additionally, information of this type is generally considered proprietary by manufacturers.

Information sources indicate that rotary kiln incinerators generally have a length to diameter ratio (L/D) between 2 and 10. Smaller L/D ratios result in less particulate carry over. Rotational speeds of the kiln are usually much slower than those for kilns which are utilized as calciners or dryers and are on the order of 1 to 5 feet per minute measured at the kiln periphery. Both the L/D ratio and the rotational speed are strongly dependent upon the type of waste being combusted. In general, larger L/D ratios along with slower rotational speeds are used when the waste material requires longer residence times in the kiln for complete combustion.[1701]

The residence time and combustion temperature required for proper incineration is totally dependent upon the waste materials combustion characteristics. Combustion temperatures usually range from 1,600 F to 3,000 F. Required residence times vary from seconds to hours. For instance, a finely divided propellant may require 0.5 seconds while wooden boxes, municipal refuse, and railroad ties may require 5, 15 and 60 minutes respectively.[1701]

When it is desired to increase the capacity of an existing kiln incinerator, consideration should be given to the following changes:[1673,1701]

(1) Increase charge to the kiln.

(2) Increase temperature and quantity of combustion gases.

(3) Decrease quantity of air in excess of combustion needs.

(4) Increase speed of rotation of kiln.

(5) Increase capacity of feeding and discharge mechanisms.

(6) Decrease moisture content of feed material.

(7) Increase temperature of feed material.

(8) Preheat all combustion air.

(9) Reduce leakage of cold air into kiln.

(10) Increase stack draft by increasing height or by use of jets.

(11) Install instrumentation to control the kiln at maximum-capacity conditions.

Efficient air seals are essential for the controlled and economical operation of kiln incinerators. They reduce outside air entrance; certain types effectively prevent entrance of all outside air. The inflow of air is the result of the kiln incinerator operating under reduced pressures which are caused by downstream induced draft fans and thermal lift from the stack. This reduced pressure is necessary to ensure against any leakage of undesirable material to the surroundings.[1673,1701]

The simplest type of air seal is a floating T-section ring mounted on a wearing pad around the feed end of the kiln shell. The web of the T-ring is confined within circular retainer plates (Figure 13). The floating-type discharge-end air seal consists of a circular bar which floats on a wearing pad and which can be moved to provide the desired operating clearance between air seal and support. The floating ring and the fixed portion of these seals can be furnished with renewable wearing surfaces. Air infiltration through this type of seal is usually less than 10 percent. For further reduction of air infiltration, lantern-ring-type floating seals, pressurized with inert gas or stack gases, are employed.[1673,1701]

Process Economics. Capital and operating cost data on rotary kiln incineration systems are scarce. The installed capital investment will vary significantly depending upon the type and quantity of waste being incinerated, the quantity and sophistication of water and air correction equipment, waste pretreatment equipment, materials of construction and the extent of heat recovery equipment. Operating costs are mostly dependent upon the amount of secondary fuel required, replacement of refractory linings (usually about once per year), heat recovery and labor.

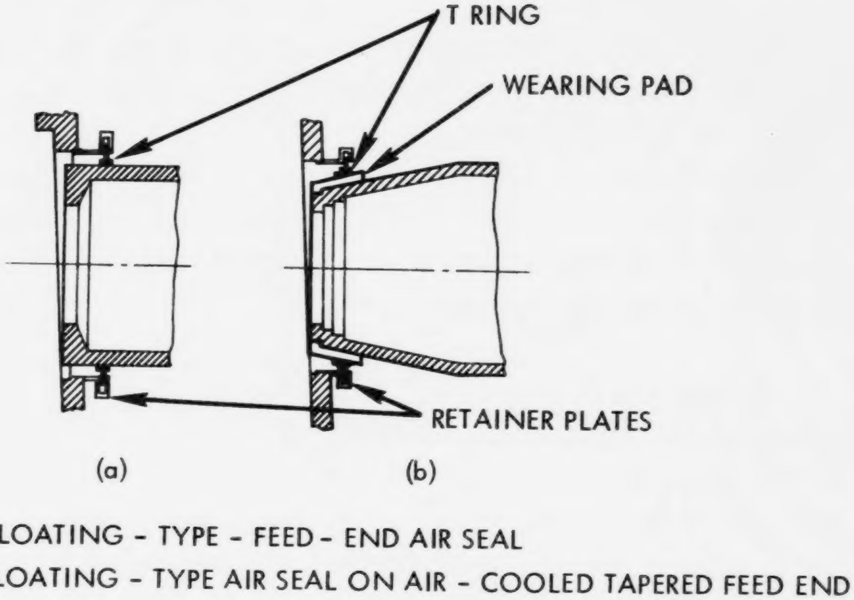

T RING
WEARING PAD
RETAINER PLATES
(a)
(b)
(a) SINGLE - FLOATING - TYPE - FEED - END AIR SEAL
(b) SINGLE - FLOATING - TYPE AIR SEAL ON AIR - COOLED TAPERED FEED END

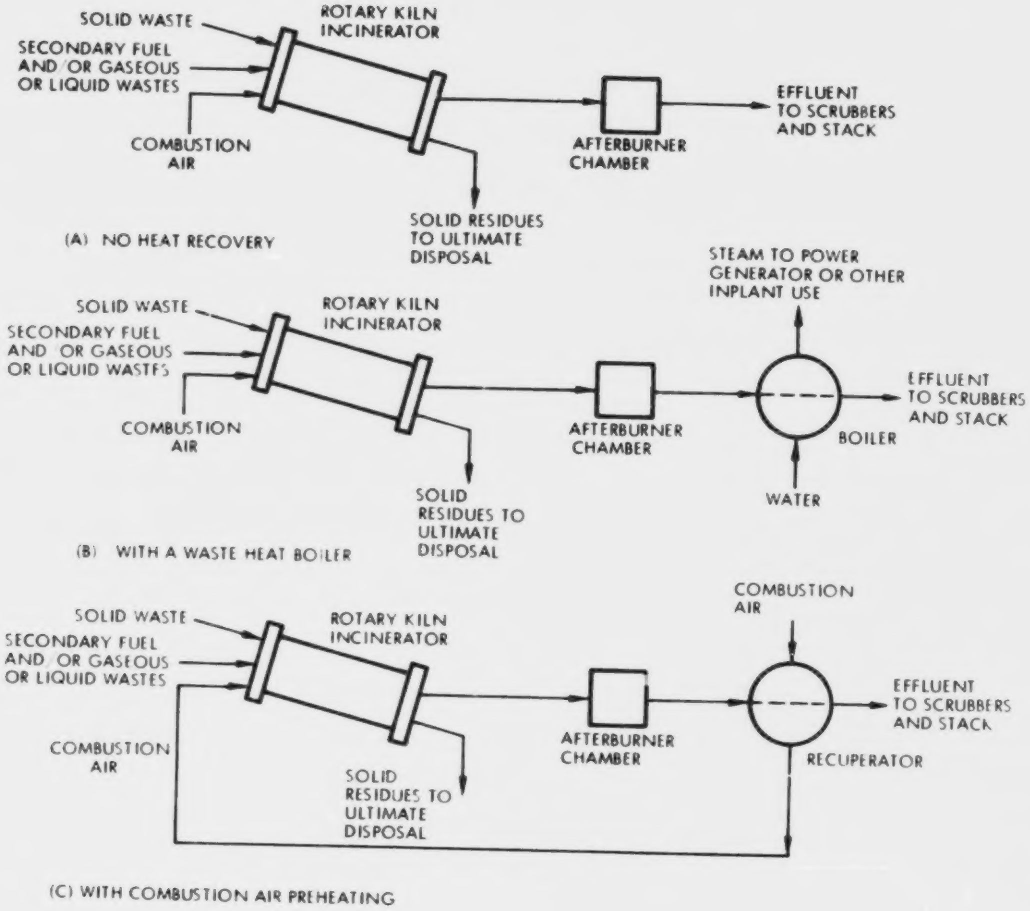
Figure 13. Kiln Seal Arrangements[1673,1701]

Uninstalled costs of the rotary kiln itself are reported to run between $30 and $60 per cubic foot of kiln.[1674,1701] Installation is generally about 200 percent of the purchased cost.[1674] Kiln maintenance averages 5 to 10 percent of the total installed cost per year but is dependent largely on the life of the refractory lining.[1673] These costs do not take into account secondary combustion chambers, heat recovery equipment or air correction equipment.

Installed costs for large municipal type rotary kiln incineration systems (as discussed in the section on Operation Principle) are on the order of $10,000 per daily ton of feed capacity.[0582] This cost includes waste heat broilers utilized for steam generation. The installed cost of relatively small industrial type rotary kiln incinerator systems (as presented in Figure 13) range from $2,500 to $5,000 per daily-ton of feed capacity, depending on the specific application.[1701]

Process Modifications.[0053,0582,1701] Basically, the only process modification utilized in rotary kiln incineration is waste heat recovery (Figure 14). This practice is seldom followed in industrial and military applications due to the expense of heat recovery equipment and the fluctuations incurred in both waste feed quantity and composition. There have been instances however, when waste heat boilers have been used to recover heat from gaseous effluents where there is need for steam elsewhere on the industrial site. In these cases, the incinerators also function as boilers and constant heat output must be maintained through the use of auxiliary fuels.

Large municipal installations generally utilize heat recovery either for power generation or preheating of combustion air. In the latter case, a significant increase in incineration capacity can be realized. These alternatives are generally economically attractive because of the large volumes of waste(refuse) and the relatively constant heat content of the waste (usually 4800 to 6500 Btu/pound).


SOLID WASTE
SECONDARY FUEL AND/OR GASEOUS OR LIQUID WASTES
COMBUSTION AIR
ROTARY KILN INCINERATOR
SOLID RESIDUES TO ULTIMATE DISPOSAL
AFTERBURNER CHAMBER
EFFLUENT TO SCRUBBERS AND STACK
SOLID WASTE
SECONDARY FUEL AND/OR GASEOUS OR LIQUID WASTES
COMBUSTION AIR
ROTARY KILN INCINERATOR
SOLID RESIDUES TO ULTIMATE DISPOSAL
AFTERBURNER CHAMBER
STEAM TO POWER GENERATOR OR OTHER INPLANT USE
BOILER
WATER
EFFLUENT TO SCRUBBERS AND STACK
SOLID WASTE
SECONDARY FUEL AND/OR GASEOUS OR LIQUID WASTES
COMBUSTION AIR
ROTARY KILN INCINERATOR
SOLID RESIDUES TO ULTIMATE DISPOSAL
AFTERBURNER CHAMBER
COMBUSTION AIR
RECUPERATOR
EFFLUENT TO SCRUBBERS AND STACK

(A) NO HEAT RECOVERY

(B) WITH A WASTE HEAT BOILER

(C) WITH COMBUSTION AIR PREHEATING

Figure 14. Heat Recovery Options

Process Applicability. The rotary kiln incinerator is generally applicable to the ultimate disposal of any form of combustible waste material and represents proven technology. It can incinerate combustible solids (including explosives), liquids (including chemical warfare agents), gases, sludges and tars. For that reason, it is very likely that a National Disposal Site would contain a large industrial type rotary kiln incinerator installation such as the one operated by the Dow Chemical Company at Midland, Michigan (discussed in the Section on Operation Principle). The National Disposal Site facility would require the addition of highly efficient secondary abatement equipment such as scrubbers and precipitators.

Liquid Waste Combustors

Liquid waste combustors are versatile units which can be used to dispose of virtually any combustible liquid waste with a viscosity less than 10,000 SSU. There are a wide variety of liquid waste combustors presently marketed, however they are generally classified as being either horizontal or vertical incineration units. These units have found wide usage throughout the manufacturing industries.

Operation Principle.[0304] Before a liquid waste can be combusted, it must be converted to the gaseous state. This change from a liquid to a gas occurs inside the combustion chamber and requires heat transfer from the hot combustion product gases to the injected liquid. In order to effect a rapid vaporization (i.e., increase heat transfer), it is desirable to increase the exposed liquid surface area. Most commonly the amount of surface exposed to heat is increased by finely atomizing the liquid to small droplets of 40μ size or smaller. This atomization can be achieved mechanically, by two phase flow, or by a combination of both methods. It is usually achieved in the liquid burner directly at the point of fuel and air mixing.

Atomization is the heart of any good liquid incinerator. Mechanical means of atomization include rotary cup and pressure atomization. The rotary cup consists of an open cup mounted on a hollow shaft. The cup is spun rapidly and liquid admitted through the hollow shaft. A thin film of the liquid to be atomized is centrifugally torn from the lip of the cup and surface tension reforms it into droplets. To achieve conical shaped flames an annular high velocity jet of air (primary air) must be directed axially around the cup. If too little primary air is admitted the fuel will impinge on the sides of the incinerator. If too much primary air is admitted the flame will not be stable, and will be blown off the cup. For fixed firing rates, the proper adjustment can be found and the unit operated long periods of time without cleaning.

Pressure atomizing may take many forms. The familiar garden hose nozzle is one example. Most commonly the liquid is given a direction by internal tangential guide slots to the center of the nozzle and then released axially through an orifice. Good atomization can be achieved at moderate pressures (100 to 150 psi). Disadvantages include a limited variable flow range at low pressures and, especially in the smaller sizes, a tendency to plug with foreign matter. Large sizes are reasonably free from this problem.

Two-fluid nozzles may be used to impinge a compressible gas on a liquid to tear it into small particles. The compressible gas may be air, nitrogen, steam, etc. Steam is quite commonly used as a low cost source of compressed gas. These nozzles may take three forms: internal mix, external mix or sonic.

As the name implies, internal mix nozzles impinge the gas and liquid before it is sprayed from the nozzle. External mix nozzles impinge jets of gas and liquid together outside of the nozzle body. Sonic nozzles (Figure 15) use the compressed gas to create high frequency sound waves which are directed on the liquid streams. The liquid passage is large in diameter and requires little pressure drop. It can handle slurries or large particles without pluggage. Most two-phase nozzles can operate long periods without

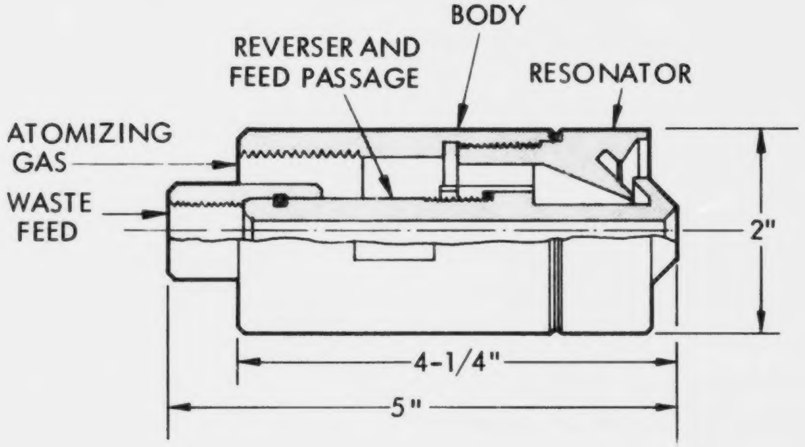

BODY
REVERSER AND FEED PASSAGE
RESONATOR
ATOMIZING GAS
WASTE FEED
2"
4-1/4"
5"

Figure 15. Typical Sonic Nozzle[0304]

difficulty and without cleaning. A common consumption figure is 1/2 scfm of compressed gas per gph of fluid atomized.

Liquid burners require considerably more turbulence and time to complete combustion than do gas burners. To complete combustion violent turbulence of the droplets is desirable, and the larger the particles, the greater distance they will go before being completely vaporized and burned. For this reason, forced draft units, if well designed, will have better combustion characteristics than natural draft units. Burners must also be located to prevent flame impingement on walls and, in the case of multi-burner units, interference with one another. While multiple atomizers can be located within a single air register, the performance will suffer, and combustion volume must be added to offset this characteristic. Whenever possible, the number of liquid streams should be minimized.

Liquid streams can carry impurities of every sort. Futhermore, they may be highly viscous, which makes handling and atomizing difficult. Liquids should generally have a viscosity of 10,000 SSU or less to be satisfactorily pumped and handled in pipes. For atomization, they should have a maximum viscosity of 750 SSU. If the viscosity exceeds this value the atomization may not be fine enough, and the resultant droplets of unburned liquid may cause smoke or other unburned particles to leave the unit. Viscosity can usually be controlled by heating with tank coils or in-line heaters. Should gases be evolved in any quantity before the desired viscosity is reached, they may cause unstable fuel feed and burning. If this occurs, the gases should be trapped and vented safely, either to the incinerator or elsewhere. If preheating is not feasible, a lower viscosity and miscible liquid may be added to reduce the viscosity of the mixture.

Prior to heating a liquid waste stream, a check should be made to insure that undesirable preliminary chemical reactions such as polymerization, nitration, oxidation, etc., will not occur. Should these occur, it may be more desirable to fill disposable containers with the liquid and treat them as solids. Other preparatory steps may include filtration, degassing, pressurizing, neutralizing, storage, mixing, etc. In every one of these steps care must be employed to see that undesired and harmful results do not occur. Pump and piping materials of construction must be suitable for the liquids encountered. Heated liquids that can solidify or become too viscous should have jacketed or traced piping. Provision should be made to clean out the piping and equipment when long shutdowns occur. This is usually done by purging with steam. Certain atomizing nozzles should always be blown clear with steam whenever flow is stopped. If not, the residual heat in the incinerator may cause thermal cracking of the liquid remaining in the nozzles, resulting in partial or complete pluggage.

Process Design. There are basically two forms of liquid waste incinerators; vertically and horizontally fired units. Units, regardless of form, usually operate at temperatures ranging from 1,200 F to 3,000 F (most units operate around 1,600 F) and residence times ranging from 0.5 to 1.0 second. Most units have combustion chamber volumes which provide for a heat release of approximately 25,000 Btu/hr-ft^3, however, the vortex type liquid combustor has an unusually high heat release of about 100,000 Btu/hr-ft^3.

A typical horizontally fired liquid waste incineration system is presented (Figure 16). This particular system is the one operated by the Dow Chemical Company at their Midland, Michigan facility. The unit is a 81 million Btu/hr incinerator which has a combustion chamber 35 ft. long and 10 ft square in cross section. Residue are fed to the unit through a combination of four dual-fired nozzles. Combustion gases are quenched in a spray chamber, followed by a high-pressure-drop venturi scrubber, and a cooler/mist-eliminator. About 1000 gpm of water is recycled from the primary tanks to the wastewater treatment facilities to furnish scrubbing water. This water flows back to the wastewater plant for treatment. About 1,100 hp. is required for this unit.[1002]

The majority of the liquid wastes treated in the Dow unit are solids at room temperature and must be kept hot in order to remain liquid. Many residues are chlorinated and can contain as high as 50 percent chlorine, plus several percent of ash in the form of Fe, Ca, Mg, Na, oxides and chlorides.[1002]

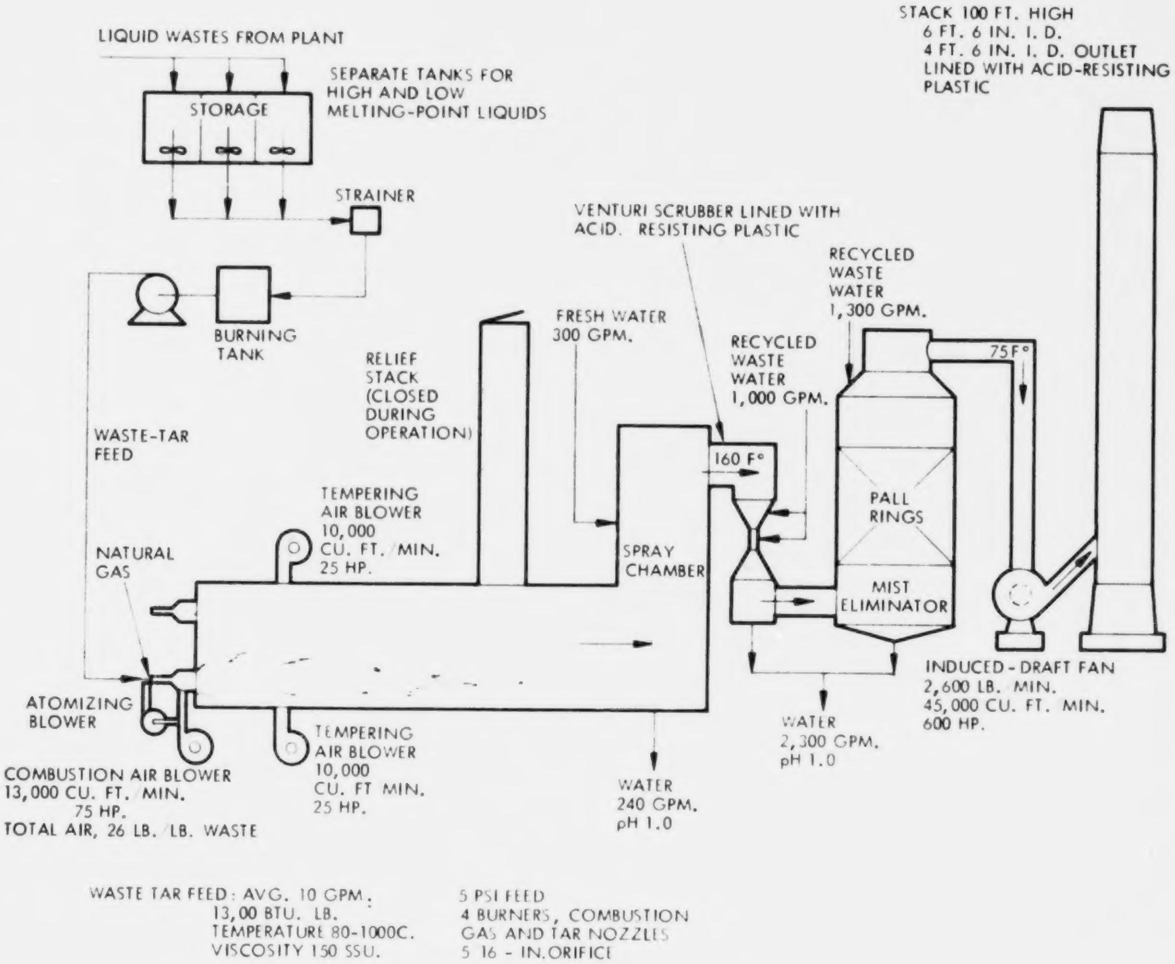

LIQUID WASTES FROM PLANT
STORAGE
SEPARATE TANKS FOR HIGH AND LOW MELTING-POINT LIQUIDS
STRAINER
BURNING TANK
WASTE-TAR FEED
NATURAL GAS
ATOMIZING BLOWER
COMBUSTION AIR BLOWER 13,000 CU. FT. MIN. 75 HP.
TOTAL AIR, 26 LB. LB. WASTE
TEMPERING AIR BLOWER 10,000 CU. FT. MIN. 25 HP.
TEMPERING AIR BLOWER 10,000 CU. FT MIN. 25 HP.
RELIEF STACK (CLOSED DURING OPERATION)
FRESH WATER 300 GPM.
SPRAY CHAMBER
WATER 240 GPM. pH 1.0
VENTURI SCRUBBER LINED WITH ACID. RESISTING PLASTIC
160 F°
RECYCLED WASTE WATER 1,000 GPM.
RECYCLED WASTE WATER 1,300 GPM.
PALL RINGS
MIST ELIMINATOR
WATER 2,300 GPM. pH 1.0
75F°
INDUCED - DRAFT FAN 2,600 LB. MIN. 45,000 CU. FT. MIN. 600 HP.
STACK 100 FT. HIGH 6 FT. 6 IN. I. D. 4 FT. 6 IN. I. D. OUTLET LINED WITH ACID-RESISTING PLASTIC
WASTE TAR FEED: AVG. 10 GPM. 13,00 BTU. LB. TEMPERATURE 80-1000C. VISCOSITY 150 SSU.
5 PSI FEED 4 BURNERS, COMBUSTION GAS AND TAR NOZZLES 5 16 - IN. ORIFICE

Figure 16. Horizontally Fired Liquid Waste Incineration System[1002]

A typical vertically fired liquid waste incinerator is presented (Figure 17). This particular unit is designed and marketed by the Prenco Division of Pickands Mather and Company. It is a versatile system in that it can be brought up to operating temperature (1,600 to 3,000 F, depending on type of waste material to be destroyed) in one to two hours with minimal fuel requirements. This quick warm-up permits periodic rather than continual operation.[0976]

The Prenco vertical combustor operates in the following manner. A mixture of auxiliary fuel (usually natural gas) and high pressure air are first fed into the vertical retort to bring it up to proper waste decomposition temperature. When the retort reaches the correct temperature, as determined by the temperature measuring instruments, fuel flow is modulated and waste is admitted to the air-waste entrainment compartment. From there the aerated waste is fed into a turbulence compartment where it is mixed with more high pressure air and injected into the high-temperature vertical retort. Here the process breaks down the waste by molecular dissociation, oxidation, and ionization. The gases and any inert particles produced flow vertically through the air cone and out of the top of the retort.[0976]

Decomposition efficiency is greatly increased through the injection of pressurized air at a point near the top of the retort through ports in a specially designed refractory module. The air cone, which serves as a fuel saver, increases decomposition efficiency by increasing heat retention. It also provides additional air for an after-burner effect. In addition, the air cone reduces the temperature of the decomposed effluent to about 650 F. As a result, scrubbers and effluent test equipment can be utilized if desired.[0976]

The Prenco unit utilizes air pretreatment. Intake of air from the top of the upper nacelle causes it to be pre-heated as it travels down the outer wall of the decomposition chamber to both the turbo-blower and after-burner fans. The use of preheated air significantly increases decomposition efficiency and economy of operation.

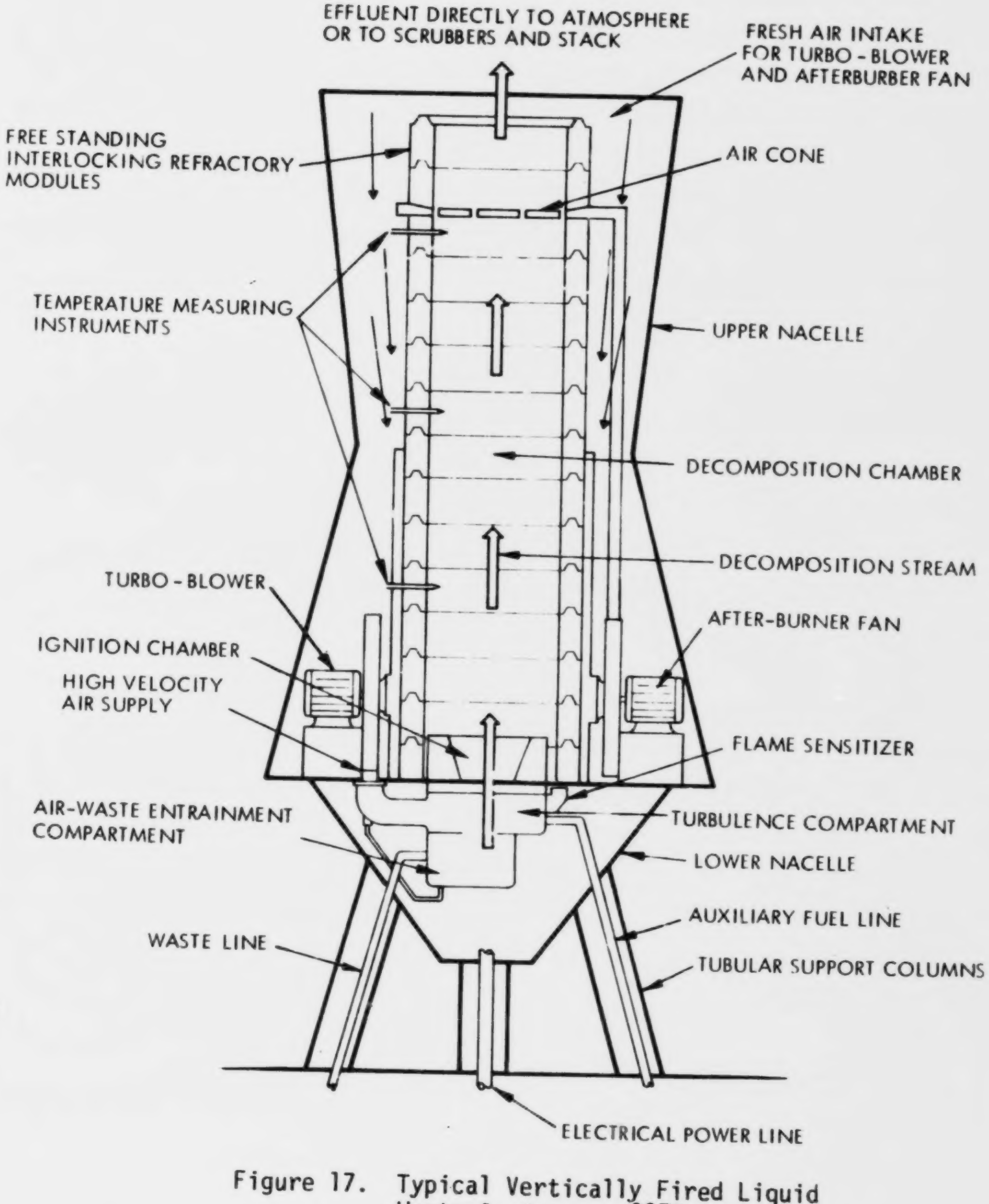

EFFLUENT DIRECTLY TO ATMOSPHERE
OR TO SCRUBBERS AND STACK
FRESH AIR INTAKE
FOR TURBO - BLOWER
AND AFTERBURBER FAN
FREE STANDING
INTERLOCKING REFRACTORY
MODULES
AIR CONE
TEMPERATURE MEASURING
INSTRUMENTS
UPPER NACELLE
DECOMPOSITION CHAMBER
DECOMPOSITION STREAM
TURBO - BLOWER
AFTER-BURNER FAN
IGNITION CHAMBER
HIGH VELOCITY
AIR SUPPLY
FLAME SENSITIZER
AIR-WASTE ENTRAINMENT
COMPARTMENT
TURBULENCE COMPARTMENT
LOWER NACELLE
AUXILIARY FUEL LINE
WASTE LINE
TUBULAR SUPPORT COLUMNS
ELECTRICAL POWER LINE

Figure 17. Typical Vertically Fired Liquid Waste Incinerator[0976]

A fairly unique form of liquid waste incinerator is the vortex combustor (Figure 18). Its unusual characteristic is its high heat release capability (about 100,000 Btu/hr-ft^3). The vortex combustor is a cylindrical furnace which is tangentially fired with a modified oil burner. In operation, the furnace is preheated for 1 hr. to a temperature of 800 to 1000 F. Operating temperature is 1,200 to 1,600 F, with 20% excess air. Liquid wastes, fuel gas and primary air pass through a hot ignition tunnel. Tangential firing creates a vortex of hot gas and primary air that flow upward through the hot combustion chamber. As the gases rise, preheated high-velocity secondary air is introduced from tangential tuyeres, maintaining the vortex. The high heat release of this unit has resulted in some slagging and erosion of the refractory.[0285,0582]

Process Economics. Installation and operating costs will vary significantly depending upon the type and quantity of waste to be processed, the amount and the sophistication of any water and/or air correction equipment required, waste pretreatment requirements, materials of construction and the extent of heat recovery. Liquid waste incineration costs are reported to range between $1 and $100 per 1,000 gal. of waste incinerated depending upon system complexity.[0534,1661]

Process Modification. The primary process modifications utilized in liquid waste incineration are waste heat recovery options and burner design options. The principle heat recovery options are primary combustion air preheat through heat exchange with the hot gaseous effluent and waste heat boiler utilization (Figure 19). Waste heat boilers are generally used only when there is a demand for steam elsewhere on the industrial site and furthermore, heat recovery is any form is usually only considered economical for large installations.[1460,1703]

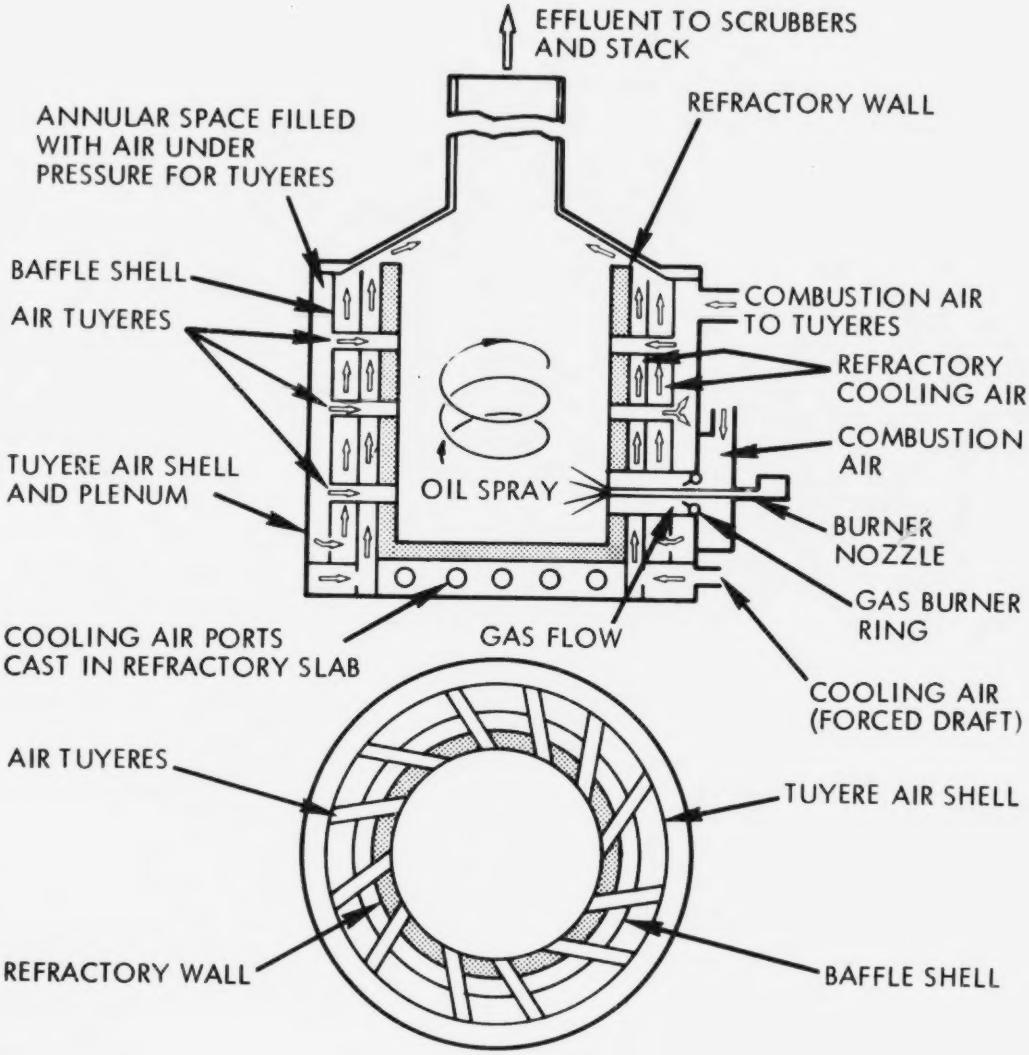
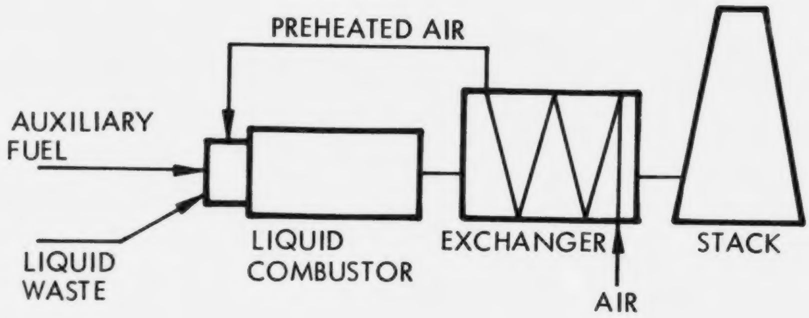
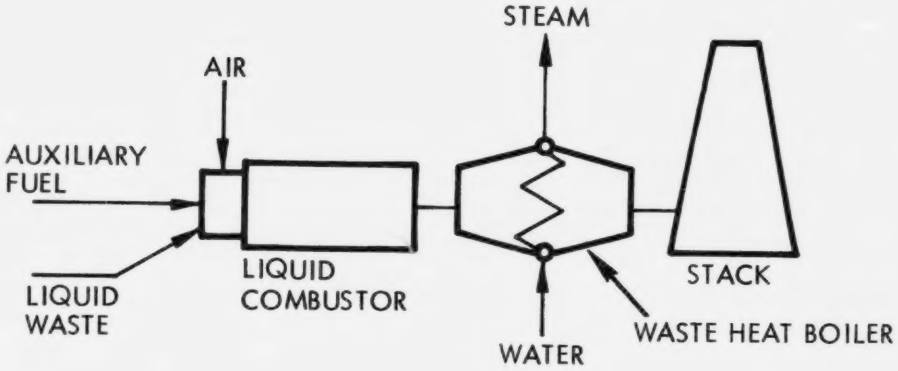

EFFLUENT TO SCRUBBERS AND STACK
ANNULAR SPACE FILLED WITH AIR UNDER PRESSURE FOR TUYERES
REFRACTORY WALL
BAFFLE SHELL
AIR TUYERES
COMBUSTION AIR TO TUYERES
REFRACTORY COOLING AIR
COMBUSTION AIR
TUYERE AIR SHELL AND PLENUM
OIL SPRAY
BURNER NOZZLE
GAS BURNER RING
COOLING AIR PORTS CAST IN REFRACTORY SLAB
GAS FLOW
COOLING AIR (FORCED DRAFT)
AIR TUYERES
TUYERE AIR SHELL
REFRACTORY WALL
BAFFLE SHELL

Figure 18. Vortex Liquid Waste Incinerators[0285,0582]


PREHEATED AIR
AUXILIARY FUEL
LIQUID WASTE
LIQUID COMBUSTOR
EXCHANGER
AIR
STACK

(A) COMBUSTION AIR PREHEAT


STEAM
AIR
AUXILIARY FUEL
LIQUID WASTE
LIQUID COMBUSTOR
WATER
WASTE HEAT BOILER
STACK

(B) WASTE HEAT BOILER UTILIZATION

Figure 19. Heat Recovery Options[1703]

The other major process modification is that of utilizing various types of burners for specific applications. Some liquid incineration units utilize very simple burners which are no more than a set of pipes; one injecting the combustible liquid waste under pressure and the other injecting air. This configuration is generally not very efficient and is usually very specific in application (i.e., designed for a specific waste material with specific characteristics and feed rate). More sophisticated burners such as the John Zink Series DB-O liquid waste burner, are designed for combination firing of auxiliary fuel gas with waste liquid and waste gas or waste liquid only. This type of burner uses steam to atomize the waste liquid and can handle liquids and slurries with viscosities up to 1,000 SSU. Inlet liquid pressures are variable (40 to 300 psi) as are atomizing steam requirements (.15 lb to .4 lb of steam per pound of waste) depending upon the characteristics of the waste liquid. These burners may be equipped with pilot burners and electric ignitors.[1456,1460,1702]

Another type of complex burner is the TRW Combustor, designed and marketed by TRW Systems. It utilizes a central element injection technique which was first developed for rocket engines and has subsequently been adapated to the disposal of hazardous liquid wastes on a pilot scale. The burner has been used to combust a wide range of materials including solid waste, liquids and gaseous fuels. Some of the reactants which have been combusted in this type burner are presented (Table 9).

The basic injector design is a single central element configuration wherein air is injected as a continuous cylindrical sheet which impinges with fuel jets injected radially outward. The air and fuel mixture is then further mixed by means of a deflector on the control element. This deflector serves both to complete the mixing process and as a flame holder. This burner design produces an externally premixed flame with a short reaction zone.

Due to the premixed flame and short reaction zone, the TRW burner has the added feature of reducing NO_x formation. It has been demonstrated

TABLE 9
TRW BURNER APPLICATIONS

Reactants	State	Combustor Pressure (psia)	Supply Temperature (F)
Indonesian Crude Oil/Air	Liquid-gas	14.7	70
Kerosene/Air	Liquid-gas	14.7	70
$LPG/LF_2/LO_2$	Gas-liquid	100 to 50	-300 to 70
$N_2H_4/ClF_3,ClF_5$	Liquid-liquid	300	70 Fuel/-300 Ox
$UDMH/N_2O_4$	Liquid-liquid	50 to 300	40 to 90

while using fuel oil as a fuel, that NO_x concentrations are cut by as much as 75 percent when the proper amount of excess air is used (Figure 20).

Process Applicability. Liquid waste incinerators are generally applicable to the ultimate disposal of most forms (including dilute) of combustible liquid waste materials and represent proven technology. Some of the materials currently being disposed with this type incinerator are presented (Table 10).

Because of their versatility, it is likely that some form of liquid waste incinerator (as discussed in the Section on Process Design) would be an intergal part of a National Disposal Site.

Open-Pit Incineration[0582,0285]

Open pit incinerators have been used to dispose of high heat content solids and liquids. These incinerators solve the problem of high heat flux by eliminating enclosure. Their chief drawbacks are the lack of confinement of combustion product effluents and relatively high particulate emissions.

Operation Principle. Open-pit incinerators vary from the pedestal-mounted oil burner used by Union Carbide to the Du Pont pit (Figure 21). The Union Carbide installation burns organic liquids containing up to 25 percent water without visible smoke. The installation consists of burners firing horizontally and mounted about 5 1/2 ft. above grade. The firing area is surrounded by earthworks for personnel protection. Heat is dissipated by direct convection and radiation. By the very nature of the design, there is always excess air.

The open-pit incinerator was orginally developed at Du Pont for the safe destruction of nitrocellulose that presents an explosion hazard in a conventional closed incinerator. The incinerator has an open top and an array of closely spaced nozzles that create a rolling action of high-velocity air over the burning zone (Figure 21). Very high burning rates, long residence times leading to complete combustion, and high flame temperatures are achieved. Visible smoke is readily eliminated and smuts

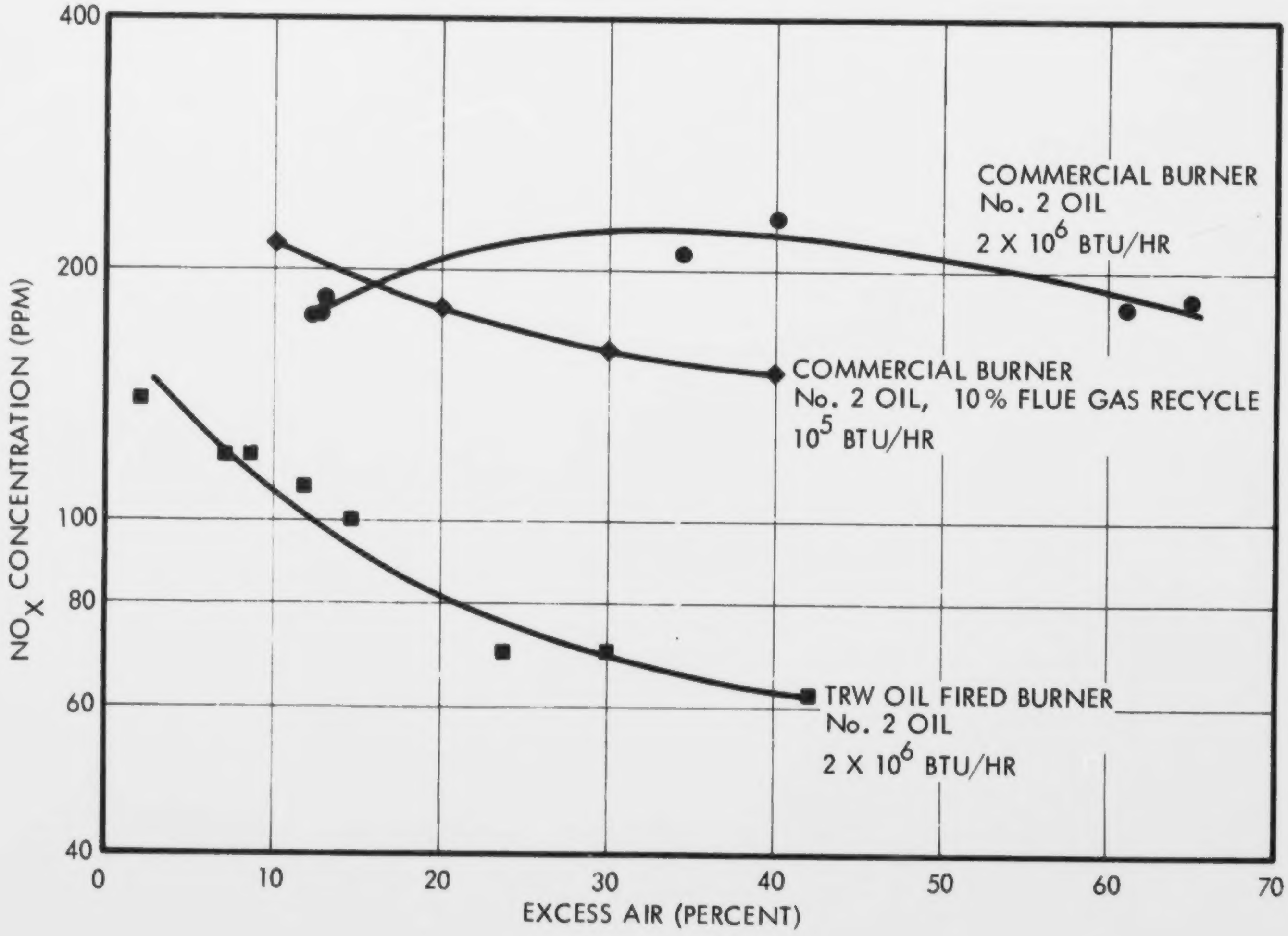


Figure 20. NO_x Concentration as a Function of Excess Air

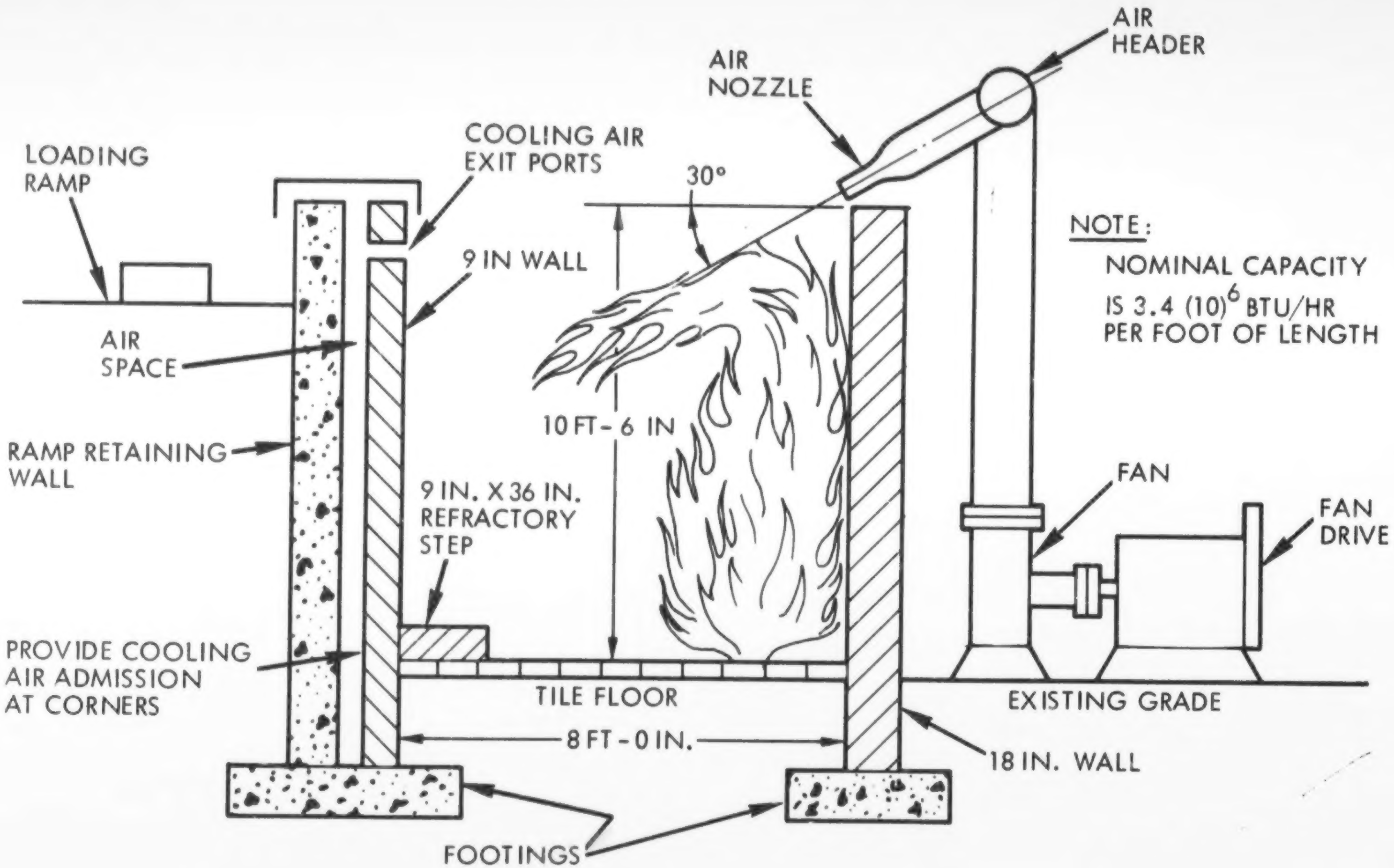

AIR HEADER
AIR NOZZLE
COOLING AIR EXIT PORTS
LOADING RAMP
30°
NOTE:
NOMINAL CAPACITY IS 3.4 (10)^6 BTU/HR PER FOOT OF LENGTH
9 IN WALL
AIR SPACE
10 FT - 6 IN
RAMP RETAINING WALL
FAN
9 IN. X 36 IN. REFRACTORY STEP
FAN DRIVE
PROVIDE COOLING AIR ADMISSION AT CORNERS
TILE FLOOR
EXISTING GRADE
8 FT - 0 IN.
18 IN. WALL
FOOTINGS

Figure 21. Du Pont Open-Pit Incinerator[0235]

TABLE 10

LIQUID WASTES CURRENTLY BURNED IN LIQUID WASTE INCINERATION

Separator Sludges
Skimmer Refuse
Oily Waste
Detergent Sludges
Digester Sludges
Cutting Oils
Coolants
Strippers
Phenols
Wine Wastes
Potato Starch
Vegetable Oils
Washer Liquids
Still & Reactor Bottoms
Soap & Detergent Cleaners
Animal Oils & Rendering Fats
Cyanide & Chrome Plating Wastes
Lube Oils
Soluble Oils
Polyester Paint
PVC Paint
Latex Paint
Thinners
Solvents
Polymers
Resins
Cheese Wastes
Dyes
Inks

are contained by proper screening. Oversized wastes and plastics that create problems in conventional incinerators are easily destroyed in the open-pit incinerator. It should be noted that the concentration of particulates is slightly higher than conventional incinerators, and there is no way to clean the exit gases. Although these pit incinerators are used for liquid wastes, they are more efficient for solid wastes, especially rubber and plastic.

Process Design. The incinerator consists of a rigid shell of either reinforced-concrete or steel, lined with refractory on the floor and walls. Empirical and theoretical calculations indicate the optimum width to be 8 ft. between refractory walls. The capacity is determined by length-usually between 8 and 16 ft. The pit is about 10 ft. with cleanout doors located at either end. Normally, a screened enclosure is placed over the pit to contain large airborne particles and for insect and rodent control when burning garbage.

The over-fire air is supplied from a manifold running along one edge of the pit, with alternating 2- and 3-inch nozzles directed downward at an angle of 25 to 35 deg. across the incinerator. Charging is from the opposite side of the nozzles from a loading ramp. The pit should be oriented so that the loading ramp is located upwind. The high-velocity air jets create turbulence in the burning zone, and the excess air aids complete combustion. When the equipment is properly operated, the air pattern creates a sheet of flame under the air manifold on the back wall, rolling the flame across the top of the pit. Particulates and unburned gases are largely returned to the burning-zone more or less eliminating smoke. Smoke intensity rarely exceeds Ringelmann #1 when properly operated.

Operating capacity of the pit depends on the lower heating value of the feed, combustion characterisitics, quantity of overfire air, size and configuration of the pit, and method of charging. Not less than 100 percent excess air is required, and 300 percent is usual. Du Pont's criteri are:

850 cu.ft./min. of overfire air at 11 in. of water column per foot of length for standard trash (5,000 Btu/lb).

The incinerators are charged intermittently by dump trucks, although hydraulic rams and skip hoists have been used. The rate of charge depends on the material being burned, in order to meet the heat-release capability of the pit. High-heating-value materials such as plastics are fed in small quantities at frequent intervals. The operator's skill is the major factor in minimizing emissions while maintaining a high burning rate.

Process Economics. Direct operating costs are low. Two men can operate two pits. The only other costs are for energy to drive the blower and operate the loader and any cleanout device. No auxiliary fuel is used, as lighting off a small amount of combustible material will ignite the pit. Maintenance is slight and largely consists of repair of the refractory.

Capital cost is low. An average price for a commercial unit 16 ft long, 8 ft wide by 10 ft deep, completely installed, including a covered storage building for the waste and a screened enclosure for the pit is about $65,000. The capacity is 5,000 lb/hr of low heat-release material, and about half that for high heat-release material.

Process Applicability. A variety of wastes have been burned in the pit incinerator. It readily accepts heavy timbers, cable reels and construction wastes. It burns plastics and similar high heat-release materials that might detonate, or erode the refractory in a closed unit. It effectively handles numerous types of manufacturing and process wastes both liquid and solid, plant trash and rubber wastes.

Although the open-pit incinerator is currently used industrially, it is not recommended for use at a National Disposal Site because of the associated lack of effluent control. This lack of control might result in emissions to the surroundings of harmful combustion products such as chlorides, fluorides, cyanides, sulfur compounds, carbon monoxide, or any partially combusted waste material.

Open Incineration[1688,1689]

Open incineration is the burning of waste materials on open land without the use of combustion equipment. This form of incineration is utilized mainly for the disposal of waste or excess high explosives. It is generally unacceptable for the disposal of other forms of waste because of the associated lack of combustion product effluent control.

Process Description. A current disposal technique utilized for many high explosive wastes such as TNT, Comp B-3, LX-09, as well as wet explosive machining waste is open burning. A typical open burning operation (conducted at the rate of about 2,000 lb per week) is to place the waste explosive and explosive contaminated waste on an asbestos pad covering a flat gravel base in a remote open area of the plant grounds. The wastes are thoroughly wet down with fuel oil and ignited from a safe distance by the use of a bridgewire and lead. Considerable black smoke along with NO_x, CO and HF are evolved (Table 11) during operation and are emitted directly to the atmosphere. These emissions are the result of uncontrolled combustion temperature, incomplete combustion due to the inability of oxygen to efficiently mix with the waste, and the inability to effect sufficient residence time of the generated particulate at elevated temperature. Because of the emission problem, there is currently an effort to develop combustion units which are applicable to explosives and incorporate effluent scrubbers.

Process Applicability. Open burning is not considered to be an adequate form of waste disposal because of the associated loss of gaseous effluent control. Although open burning is currently utilized for the disposal of explosives and explosive wastes, it is anticipated that this practice will cease when new technology is developed for this application.

TABLE 11
POLLUTION EMANATING FROM THE BURNING OF TNT, COMP B-3 AND LX-09

Pollutant	Emitted from Burning 3.8 Tons of TNT	Emitted from Burning 3.8 Tons of Comp B-3	Emitted from Burning 3.8 Tons of LX-09
Hydrocarbons	4 lb	0	0
Carbon Monoxide	213 lb	19 lb	4 lb
Oxides of Nitrogen	570 lb	141 lb	110 lb
Hydrogen Fluoride	0	0	23 lb
Soot	684 lb	0	0

Multiple Chamber Incinerators[0582,0862]

The multiple chamber incinerator has been employed by both municipal and industrial facilities for solid waste disposal.

The configuration of modern multiple chamber incinerators falls into two general types (Figures 22 and 23). These are the retort type, named for the return flow of gases through the "U" arrangement of component chambers, and the in-line type, so-called because the component chambers follow one after the other in a line. Essential features that distinguish the retort type of design are as follows:

(1) The arrangement of the chambers causes the combustion gases to flow through 90-degree turns in both lateral and vertical directions.

(2) The return flow of the gases permits the use of a common wall between the primary and secondary combustion stages.

(3) Mixing chambers, flame ports, and curtain wall ports have length-to-width ratios in the range of 1:1 to 2.4:1.

(4) Bridge wall thickness under the flame port is a function of dimensional requirements in the mixing and combustion chambers. This results in construction that is somewhat unwielding in the size range above 500 pounds per hour.

Distinguishing features of the in-line-type design are as follows.

(1) Flow of the combustion gases is straight through the incinerator with 90-degree turns only in the vertical direction.

(2) The in-line arrangement is readily adaptable to installations that require separated spacing of the chambers for operating, maintenance, or other reasons.

(3) All ports and chambers extend across the full width of the incinerator and are as wide as the ignition chamber. Length-to-width ratios of the flame port, mixing chamber, and curtain wall port cross sections range from 2:1 to 5:1.

Each style has certain characteristics with regard to performance and construction that limit its application.

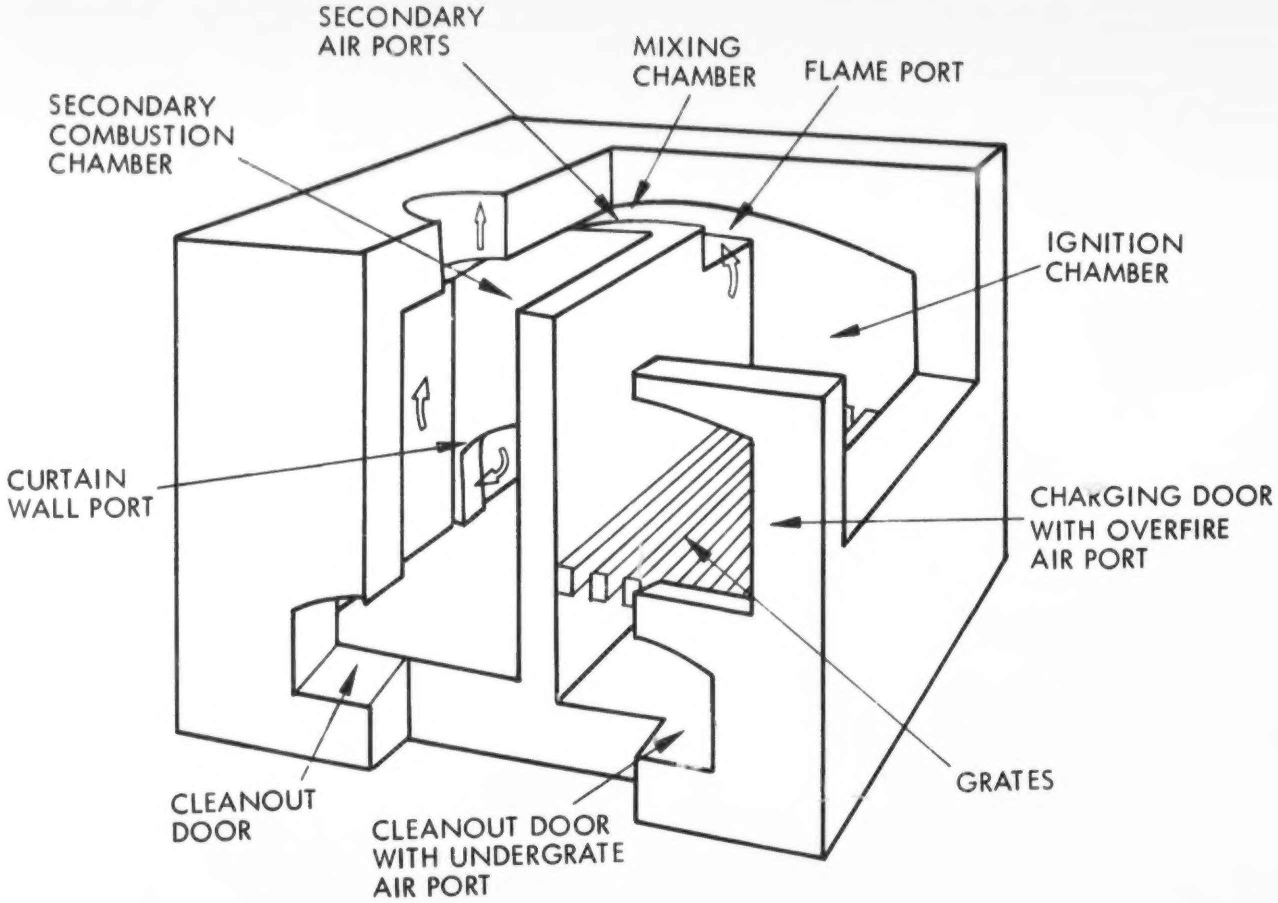

SECONDARY
AIR PORTS
MIXING
CHAMBER
FLAME PORT
SECONDARY
COMBUSTION
CHAMBER
IGNITION
CHAMBER
CURTAIN
WALL PORT
CHARGING DOOR
WITH OVERFIRE
AIR PORT
GRATES
CLEANOUT
DOOR
CLEANOUT DOOR
WITH UNDERGRATE
AIR PORT

Figure 22. Retort Multiple Chamber Incinerator[0862]

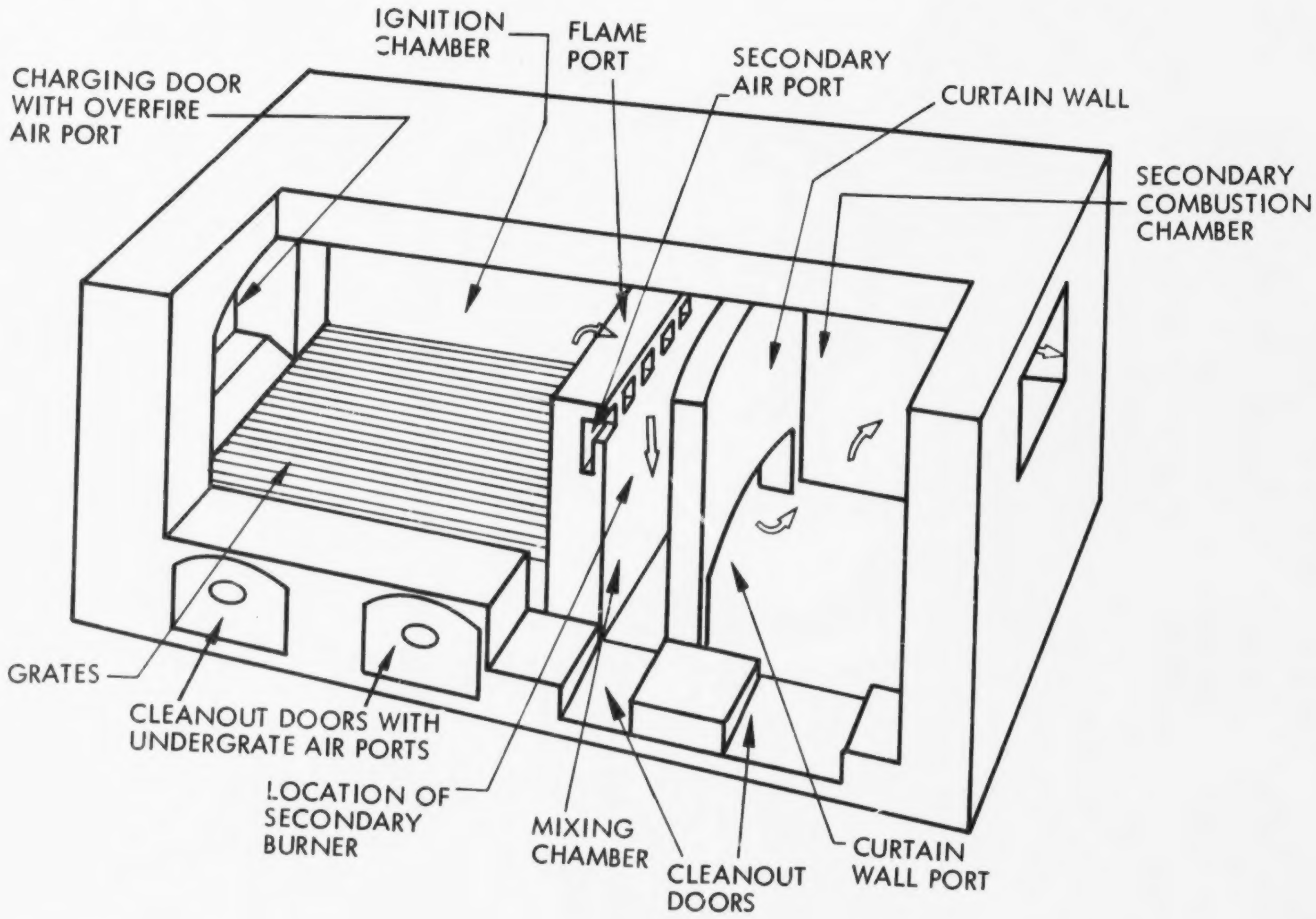

IGNITION CHAMBER
FLAME PORT
SECONDARY AIR PORT
CHARGING DOOR WITH OVERFIRE AIR PORT
CURTAIN WALL
SECONDARY COMBUSTION CHAMBER
GRATES
CLEANOUT DOORS WITH UNDERGRATE AIR PORTS
LOCATION OF SECONDARY BURNER
MIXING CHAMBER
CLEANOUT DOORS
CURTAIN WALL PORT

Figure 23. In-Line Multiple Chamber Incinerator[0862]

Operation Principle. The combustion process in a multiple chamber incinerator proceeds in two stages--primary or solid fuel combustion in the ignition chamber, followed by secondary or gaseous-phase combustion. The secondary combustion zone is composed of two parts, a downdraft or mixing chamber and an up-pass expansion or combustion chamber.

The two-stage multiple chamber incineration process begins in the ignition chamber and includes the drying, ignition, and combustion of the solid refuse. As the burning proceeds, the moisture and volatile components of the fuel are vaporized and partially oxidized in passing from the ignition chamber through the flame port connecting the ignition chamber with the mixing chamber. From the flame port, the volatile components of the waste material and the products of combustion flow down through the mixing chamber into which secondary air is introduced. The combination of adequate temperature and additional air, augmented by mixing chamber or secondary burners as necessary, assists in initiating the second stage of the combustion process. Turbulent mixing, resulting from the restricted flow areas and abrupt changes in flow direction, furthers the gaseous-phase reaction. In passing through the curtain wall port from the mixing chamber to the final combustion chamber, the gases undergo additional changes in direction accompanied by expansion and final oxidation of combustible components. Fly ash and other solid particulate matter are collected in the combustion chamber by wall impingement and simple settling. The gases finally discharge through a stack or a combination of a gas cooler (for example, a water spray chamber) and induced-draft system. Either draft system must limit combustion air to the quantity required at the nominal capacity rating of the incinerator.

The basic factors that tend to cause a difference in performance in the two incinerators are (1) proportioning of the flame port and mixing chamber to maintain adequate gas velocities within dimensional limitations imposed by the particular type involved, (2) maintenance of proper flame distribution over the flame port and across the mixing chamber, and

(3) flame travel through the mixing chamber, into the combustion chamber.

A retort incinerator in its optimum size range offers the advantages of compactness and structural economy because of its cubic shape and reduced exterior wall length. It performs more efficiently than its in-line counterpart in the capacity range from 50 to 750 lb per hour. In these small sizes, the nearly square across sections of the ports and chambers function well because of the abrupt turns in this design. In retort incinerators with a capacity of 1,000 lb per hour or greater, the increased size of the flow cross section reduces the effective turbulence in the mixing chamber and results in inadequate flame distribution and penetration and in poor secondary air mixing.

No outstanding factors favor either the retort or the in-line configurations in the capacity range of 750 to 1,000 lb per hour. The choice of retort or in-line configuration in this range is influenced by personal preference, space limitations, the nature of the refuse, and charging conditions.

The in-line incinerator is well suited to high-capacity operation but is not very satisfactory for service in small sizes. The smaller in-line incinerators are somewhat less efficient with regard to secondary stage combustion than the retort type is. In in-line incinerators with a capacity of less than 750 lb per hour, the shortness of the grate length tends to inhibit flame propagation across the width of the ignition chamber. This, coupled with thin flame distribution over the bridge wall, may result in the passage of smoke from smoldering grate sections straight through the incinerator and out of the stack without adequate mixing and secondary combustion. In-line models in sizes of 750 lb per hour or larger have grates long enough to maintain burning across their width, resulting in satisfactory flame distribution in the flame port and mixing chamber. The shorter grates on the smaller in-line incinerators also create a maintenance problem. The bridge wall is very susceptible to mechanical abuse since it is usually not provided with a structural support or backing and is thin where the secondary airlanes are located. Careless stoking and grate cleaning in the short-grate-in-line incinerators can break down the bridge wall in a short time.

The upper limit for the use of the in-line incinerator has not been established. Incinerators with a capacity of less than 2,000 pounds per hour may be standardized for construction purposes to a great degree. Incinerators of larger capacity, however, are not readily standardized since problems of construction, material usage, mechanized operation with stoking grate, induced-draft systems, and other factors make each installation essentially one of custom design. Even so, the design factors discussed herein are as applicable to the design of large incinerators as to the design of smaller units.

Process Design. Control of the combustion reaction, and reduction in the amount of mechanically entrained fly ash are most important in the efficent design of a multiple-chamber incinerator. Ignition chamber parameters are especially critical since solid contaminant discharges can be functions only of the mechanical and chemical processes taking place in the primary stage. Other important factors include the ratios of combustion air distribution, supplementary draft and temperature criteria, and portion factors. Some of these factors are functions of the desired hourly combustion rate and are expressed in empirical formulas, while others are assigned values that are independent of incinerator size. The various design factors for multiple chamber incinerators are presented (Table 12, Figures 24 and 25).

The requirement for supplementary gas burners must be determined. In general, when the moisture content of the waste is less than 10 percent by weight, burners are usually not required. Moisture contents of from 10 to 20 percent normally necessitate installation of mixing chamber burners, and moisture content of over 20 percent usually necessitate inclusion of ignition chamber burners.

TABLE 12

MULTIPLE CHAMBER INCINERATOR DESIGN FACTORS[0862]

Item and symbol	Recommended value	Allowable deviation
Primary combustion zone:		
Grate loading, L_G	10 log R_c: lb/hr-ft^2 where R_c equals the refuse combustion rate in lb/hr (refer to Figure 24.)	± 10%
Grate area, A_G	$R_c \div L_G$: ft^2	± 10%
Average arch height, H_A	$4/3 \, (A_G)^{4/11}$; ft (refer to Figure 25)	--
Length-to-width ratio (approx):		
Retort	Up to 500 lb/hr, 2:1 over 500 lb/hr. 1.75:1	--
In-line	Diminishing from about 1.7:1 for 750 lb/hr to about 1:2 for 2,000 lb/hr capacity. Over-square acceptable in units of more than 11 ft ignition chamber length.	--
Secondary combustion zone:		
Gas velocities:		
Flame port at 1,000 F	55 ft/sec	± 20%
Mixing chamber at 1,000 F	25 ft/sec	± 20%
Curtain wall port at 950 F	about 0.7 of mixing chamber velocity	--
Combustion chamber at 900 F	5 to 6 ft/sec; always less than 10 ft/sec	--
Mixing chamber downpass length, from top of ignition chamber arch to top of curtain wall port.	Average arch height, ft	± 20%
Length-to-width ratios of flow cross sections:		
Retort, mixing chamber, and combustion chamber	Range - 1.3:1 to 1.5:1	--
In-line	Fixed by gas velocities due to constant incinerator width	--

TABLE 12
MULTIPLE CHAMBER INCINERATOR DESIGN FACTORS[0862] - CONTINUED

Item and symbol	Recommended value	Allowable deviation
Combustion air:		
Air requirement batch-charging operation	Basis: 300% excess air. 50% air requirement admitted through adjustable ports: 50% air requirements met by open charge door and leakage.	--
Combustion air distribution:		
Overfire air ports	70% of total air required	--
Underfire air ports	10% of total air required	
Mixing chamber air ports	20% of total air required	--
Port sizing, nominal inlet velocity pressure	0.1 inch water gage	--
Air inlet ports oversize factors:		
Primary air inlet	1.2	--
Underfire air inlet	1.5 for over 500 lb/hr to 2.5 for 50 lb/hr.	--
Secondary air inlet	2.0 for over 500 lb/hr to 5.0 for 50 lb/hr	--
Furnace temperature:		
Average temperature, combustion products	1000 F	± 20 F
Auxiliary burners:		
Normal duty requirements:		
Primary burner	3,000 to 10,000 } Btu per lb of moisture in the waste	--
Secondary burner	4,000 to 12,000	--
Draft requirements:		
Theoretical stack draft	0.15 to 0.35 inch water gage	--
Available primary air induction draft (Assume equivalent to inlet velocity pressure.)	0.1 inch water gage.	--
Natural draft stack velocity	Less than 30 ft/sec at 900 F	--

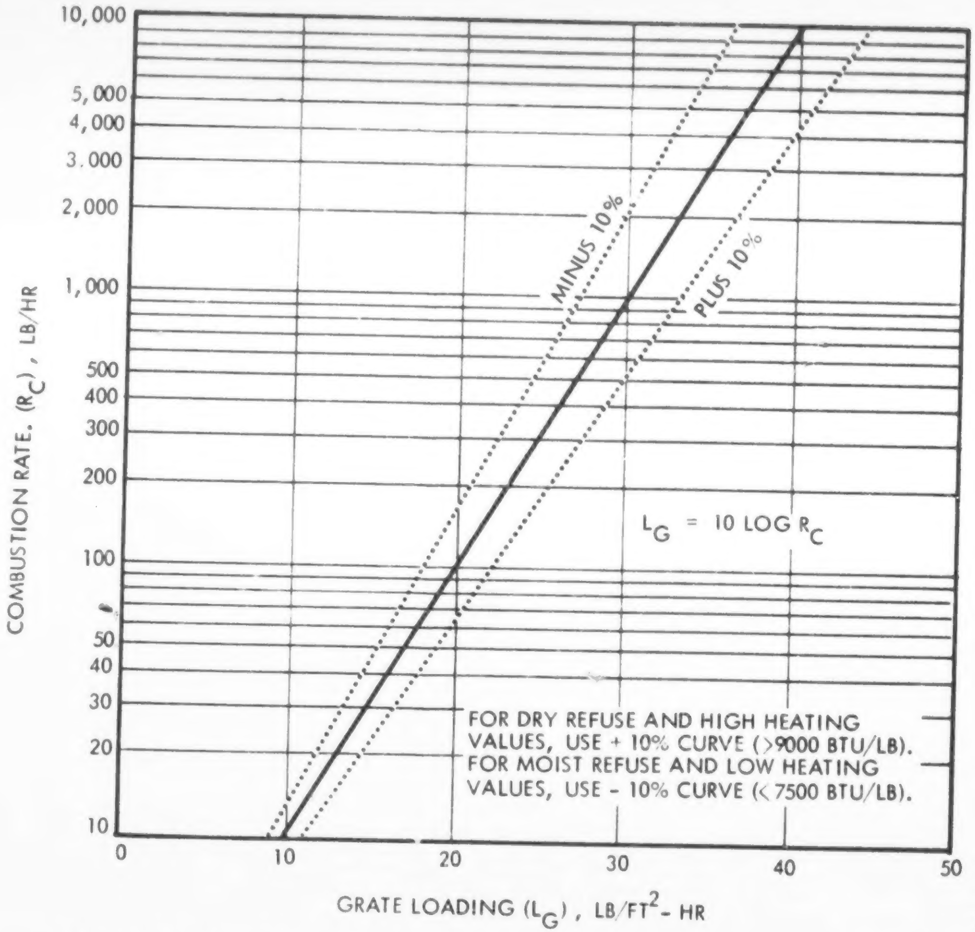


Figure 24. Relationship of Grate Loading to Combustion Rate for Multiple Chamber Incinerators.[0862]

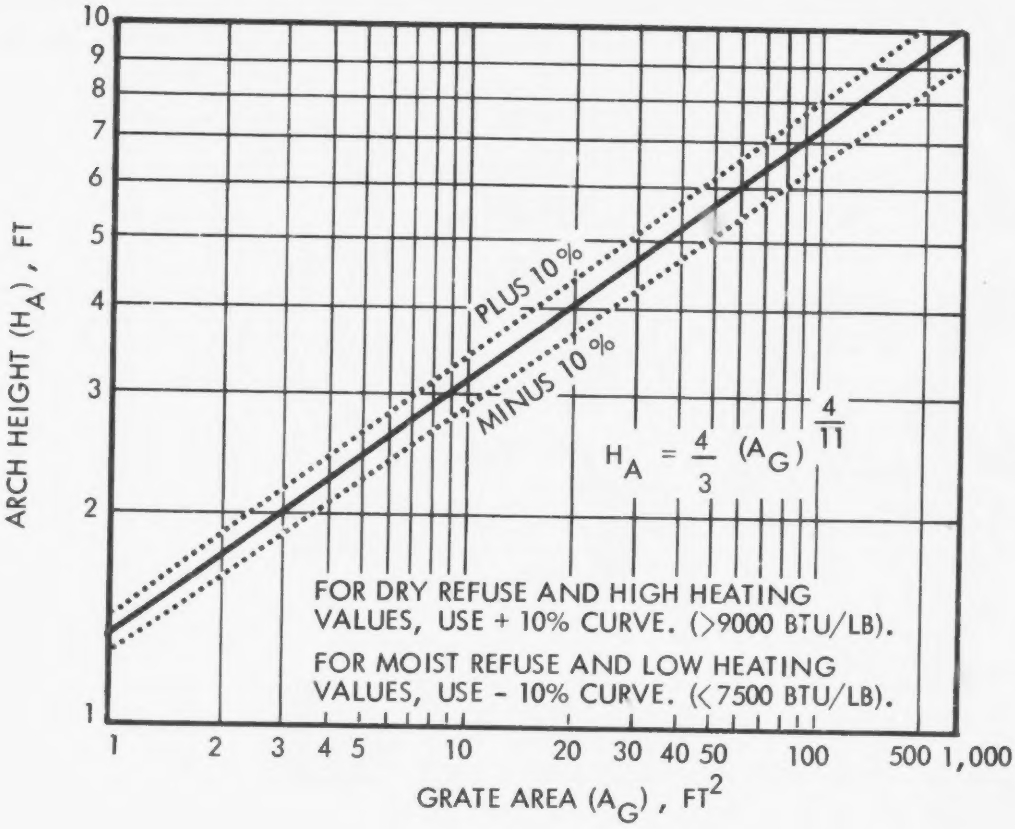


Figure 25. Relationship of Arch Height to Grate Area for Multiple Chamber Incinerators[0862]

The design and construction of multiple chamber incinerators are regulated in several ways. Ordinances and statutes that set forth basic building requirements have been established by most, if not all, municipalities. Air pollution control authorities have also set some limitations in material and construction that must be met, and manufacturers' associations have established recommended minimum standards to be followed.

The most important element in construction of multiple chamber incinerators, other than the design, is the proper installation and use of refractories. High-quality materials are absolutely necessary if a reasonable and satisfactory service life is to be expected. Manufacturers must use suitable materials of construction since faulty construction may well offset the benefits of good design. In the choice of one of the many available materials, maximum service conditions should dictate the type of lining for any incinerator. Minimum specifications of materials in normal refuse should include high-heat-duty firebrick or 120 lb per cubic foot castable refractory. These materials, when properly installed, have proved capable of resisting the abrasion, spalling, slagging, and erosion resulting from high-temperature incineration.

As the incinerator's capacity and severity of duty increase, superior refractory materials such as super duty firebrick and plastic firebrick should be employed. A recent improvement in standard construction has been the lining of all stacks with 2,000 F refractory of 2-inch minimum thickness.

The grates commonly used in multiple chamber incinerators are made of cast iron in "Tee" or channel cross section. As the size of the incinerator increases, the length of the ignition chamber also increases. In the larger hand-charged incinerators, keeping the rear section of the grates completely covered is difficult because of the greater length of the ignition chamber. The substitution of a hearth at the rear of the ignition chamber in these units has been accepted as good practice. Since surface combustion is the primary combustion principle, the use of a hearth has little effect upon combustion rate.

Installation of a sloping grate, which slants down from the front to the rear of the ignition chamber, facilitates charging. A grate such as this also increases the distance from the arch to the grates at the rear of the chamber and reduces the possibility of fly ash entrainment.

Stacks for incinerators with a capacity of 500 pounds or less per hour are usually constructed of a steel shell lined with refractory and mounted over the combustion chamber. A refractory-lined reinforced, red brick stack is an alternative method of construction when appearance is deemed important. Stacks for incinerators with a capacity of more than 500 pounds per hour are normally constructed in the same manner as those for smaller units but are often free standing for structural stability. Stack linings should be increased in thickness as the incinerator becomes larger in size.

Process Economics. Capital and operating cost data on multiple chamber incineration units are scarce. The installed capital investment will vary depending upon the type and quantity of waste being incinerated, the quantity and sophistication of air correction equipment, and materials of construction. The relative costs (as of 1968) of incinerator and air pollution control equipment of various capacities, exclusive of foundations are presented (Table 13).

Operating costs are mainly a function of labor, power, fuel and refractory repair and replacement. Multiple chamber units generally can be operated by one to two men. As of 1968, overall processing costs were reported as being \$15 to \$16 per ton of waste incinerated.

Process Applicability. Multiple chamber incinerators are generally applicable to the ultimate disposal of most forms of combustible solid waste and represent proven technology. Some of the materials currently disposed of in this type of unit are general refuse, paper, garbage, wood, phenolic resins, rubber, wire coatings, acrylic resins, epoxy resins, and polyvinyl chloride. Although the multiple chamber incinerator is capable of handling various types of solid wastes, its inability to process liquids, gases, sludges

TABLE 13

APPROXIMATE COSTS OF MULTIPLE CHAMBER INCINERATORS*

Capacity Lb /Hr	Incinerator Cost, $	Wet Scrubber Cost, $
100	1,700	3,000
150	2,000	3,600
250	2,700	4,400
500	5,000	6,200
750	9,500	7,600
1,000	12,500	8,800
1,500	20,000	11,200
2,000	25,000	13,200

*Based on 1968 costs.

and tars limits the application. Since there are other types of incineration units available which are much more diverse in application (i.e., rotary kiln fluidized bed and multiple hearth incinerators), it is doubtful that the multiple chamber incinerator would be a primary candidate for National Disposal Site utilization.

Multiple Hearth Incinerators[0285,0582,1761]

The multiple hearth incinerator (commonly called a Herreshoff furnace) is a versalite unit which has been utilized to dispose of sewage, sludges, tars, solids, gases, and liquid combustible wastes. This type of unit was initally designed to incinerate sewage plant sludges in 1934. In 1968, there were over 125 installations in operation with a total capacity of 17,000 tons per day (wet basis) for this application alone. There are currently numerous industrial installations in operation which are primarily utilized for chemical sludge and tar incineration as well as activated carbon regeneration.

Operation Principle. The multiple hearth furnace consists of a refractory-lined circular steel shell with refractory hearths located one above the other (Figure 26). Sludge and/or granulated solid combustible waste feeds through the furnace roof by a screw feeder or belt and flapgate. A rotating air-cooled central shaft with air-cooled rabble arms and teeth plows the waste material across the top hearth to drop holes. It falls to the next hearth and then the next until ash discharged at the bottom. The waste is agitated as it moves across the hearths to make sure maximum surface is exposed to hot gases. Waste grease and tars are generally fed into the furnace through side ports.

Liquid and gaseous combustible wastes may be injected into the unit through auxilliary burner nozzles. This utilization of liquid and gaseous waste represents an economic advantage since the secondary fuel (e.g., natural gas, fuel oil) requirements will be reduced thus lowering operating costs.

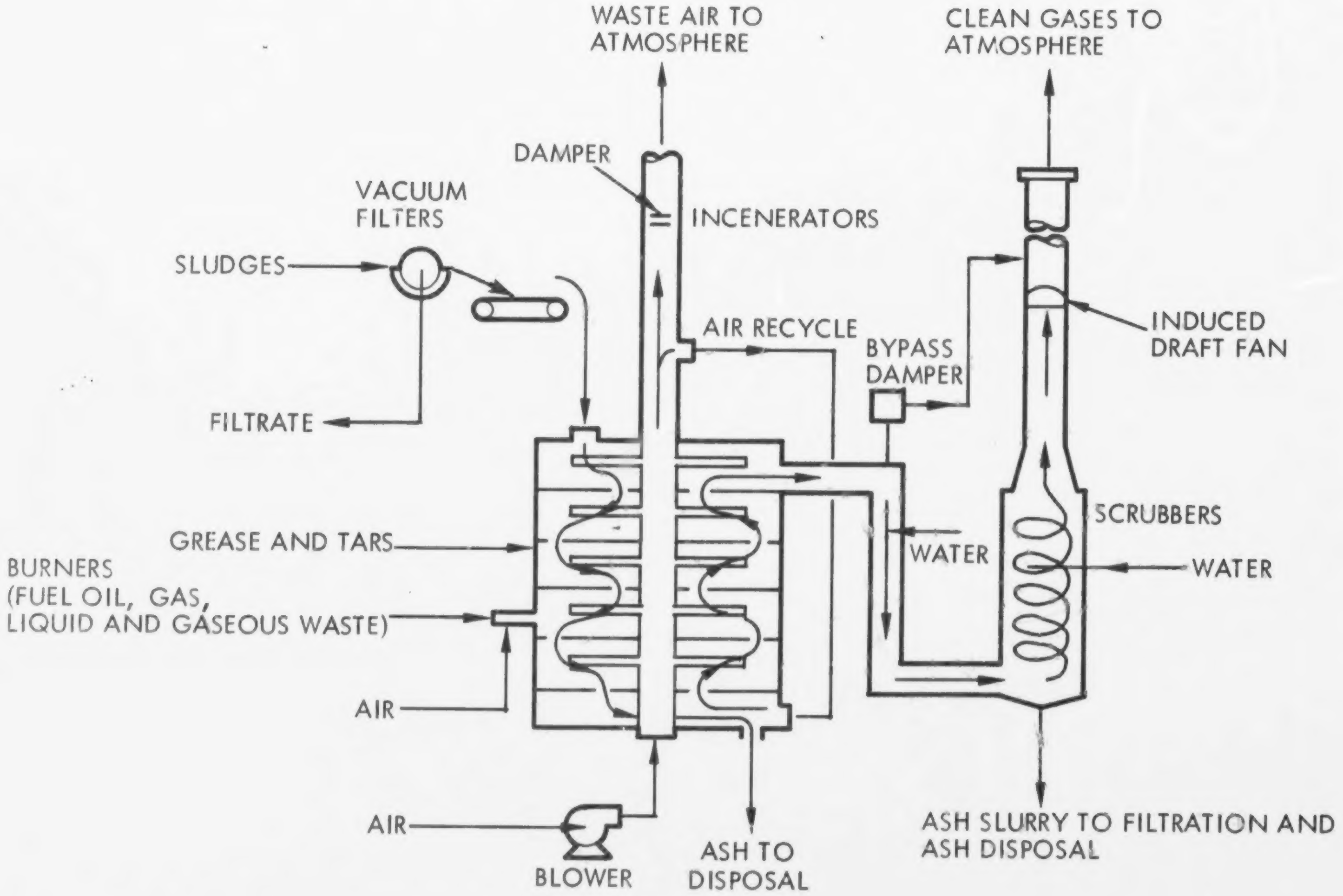

WASTE AIR TO ATMOSPHERE
CLEAN GASES TO ATMOSPHERE
DAMPER
VACUUM FILTERS
INCENERATORS
SLUDGES
AIR RECYCLE
BYPASS DAMPER
INDUCED DRAFT FAN
FILTRATE
SCRUBBERS
GREASE AND TARS
WATER
WATER
BURNERS (FUEL OIL, GAS, LIQUID AND GASEOUS WASTE)
AIR
AIR
BLOWER
ASH TO DISPOSAL
ASH SLURRY TO FILTRATION AND ASH DISPOSAL

Figure 26. Multiple Hearth Incineration System[1761]

The system has three operating zones: the top hearths where feed is dried to about 48 percent moisture; the incineration/deodorization zone, which has a temperature of 1,400 to 1,800 F; and the cooling zone, where the hot ash gives up heat to incoming combustion air. Exhaust gases exit at 500 to 1,100 F.

Incinerator ash is sterile and inert. Volume discharged from the bottom hearth is about 10 percent of the furnace feed, based on sludge cake with 75 percent moisture and 70 percent volatile content in the solids. The ash usually has less than 1 percent combustible matter, which is normally fixed carbon. Discharge can be moved hydraulically, mechanically, or pneumatically, and used as landfill or roadfill.

Current systems include gas cleaning devices on exhaust air. A number of multiple hearth incinerators are operating without difficulty in areas with strict air pollution codes. Although the exhuast does not violate opacity codes, existence of steam plumes has on occasion caused adverse public reaction.

Process Design. Most multiple hearth incinerators are primarily designed for sludge disposal. The other forms of waste which are simultaneously fed to the system are usually considered a heat source to be utilized during sludge incineration. A heat balance across a multiple hearth furnace must consider the heat absorbed by: latent heat in free moisture and combustion moisture, sensible heat in combustion gases, excess air, ash, radiation and shaft cooling. These quantities are balanced against the heat evolved from the combustibles in sludge solids and the fuel. Below is a typical analysis of sludge combustibles.

C	59.8 percent
H_2	8.5
O_2	27.5
N_2	4.2
	100.0 percent

Calorific value of this sludge is 10,000 Btu/lb.

Sludge parameters that have the most influence over incineration are moisture content, percent volatiles and inerts, and calorific value. Moisture is the principal one over which the plant operator has some control. Minimum moisture is important because of its thermal load on the incinerator.

Volatiles and inerts, which affect the Btu value of the sludge, can be controlled to some extent by treatment processes such as degritting, mechanical dewatering and sludge digestion. Almost all combustibles are present as volatiles, much in the form of grease. Volatile percentage can vary a great deal, so equipment must be designed to handle a range of values.

The sizing of a multiple hearth incinerator is dependent upon waste combustion characteristics (Table 14) and water content. Incinerator burning rates vary from 7 to 12 lb/ft^2-hr for sewage plant sludges with the value 7.5 lb/ft^2-hr generally accepted as typical. The area referred to in the burning rate is the total hearth area of the unit. Standard multiple hearth incinerator sizes range from 85 ft^2 of hearth to greater than 3000 ft^2 of hearth (Table 15). The secondary fuel requirement is dependent upon the water content of the waste being incinerated. For instance, a waste sludge with a heating value of 10,000 Btu/lb of volatile solids which is composed of 60 percent volatile solids,will require about 100 ft^3 of natural gas per ton of wet feed when the moisture content of the sludge is 75 percent. This same sludge will require about 1,200 ft^3 of gas per ton of wet sludge when the moisture content is 82.5 percent (Figure 27).

The multiple hearth incinerator is usually operated so that the top hearth temperature is in the 600 to 1,000 F range, the combustion hearths are in the 1,400 to 1,800 F range, while the cooling hearths are maintained in the 400 to 600 F range.

TABLE 14

TYPICAL COMBUSTION VALUES OF WASTE MATERIALS

Material	Combustible,%	Ash,%	Btu/lb.
Grease & scum	88.5	11.5	16,750
Fresh sewage solids	74.0	26.0	10,285
Fine screenings	86.4	13.6	8,990
Ground garbage	84.8	15.2	8,245
Rags	97.5	2.5	8,050
Digested sewage and garbage solids	49.6	50.4	8,020
Digested sludge	59.6	40.4	5,290
Grit	33.2	69.8	4,000

Note: Where organic polymers can be utilized to condition sludges, rather than ferric chlorides and lime, the heat value of the sludge cake can be increased 1,500 Btu/lb to 4,000 Btu/lb of dry solids. The ash from the furnace will also be reduced by 5 to 20 percent.

TABLE 15
STANDARD MULTIPLE HEARTH FURNACE SIZE[1761]

Outside Diameter		4 Hearth	6 Hearth	8 Hearth	10 Hearth	12 Hearth
4.5 ft (ID)	Hearth area,sq ft		85	112	140	
	Column height, ft-in.		4-0	4-0	4-0	
	Shell height, ft-in.		10-6	13-8	16-10	
	Overall height, ft-in.		15-7	18-9	21-11	
7.0 ft	Hearth area, sq ft		125	166	208	
	Column height, ft-in.		4-0	4-0	4-0	
	Shell height, ft-in.		11-10	15-5	19-0	
	Overall height, ft-in.		16-1	20-6	24-1	
8.5 ft	Hearth area, sq ft	130	193	256	319	
	Column height, ft-in.	5-0	5-0	5-0	5-0	
	Shell height, ft-in.	10-10	15-5	20-0	24-7	
	Overall height, ft-in.	16-7	21-2	25-9	30-4	
10.0 ft	Hearth area, sq ft	188	276	364	452	
	Column height, ft-in.	6-6	6-6	6-6	6-6	
	Shell height, ft-in.	10-8	15-1	19-5	23-10	
	Overall height, ft-in.	18-8	23-0	27-5	31-9	
13.5 ft	Hearth area, sq ft	390	575	760	944	1128
	Column height, ft-in.	6-6	6-6	6-6	6-6	6-6
	Shell height, ft-in.	11-8	16-7	21-5	26-4	31-2
	Overall height, ft-in.	20-8	25-6	30-5	35-3	40-2
16.0 ft	Hearth area, sq ft	573	845	1117	1305	1550
	Column height, ft-in.	7-0	7-0	7-0	7-0	7-0
	Shell height, ft-in.	13-2	18-7	24-1	29-6	35-0
	Overall height, ft-in.	22-11	28-4	33-10	39-3	44-9
18.0 ft	Hearth area, sq ft	727	1068	1410	1752	2090
	Column height, ft-in.	7-0	7-0	7-0	7-0	7-0
	Shell height, ft-in.	14-3	20-2	26-0	31-11	37-9
	Overall height, ft-in	24-3	30-1	36-0	41-10	47-9
19.5 ft	Hearth area, sq ft	863	1268	1660	2060	2464
	Column height, ft-in.	8-0	8-0	8-0	8-0	8-0
	Shell height, ft-in.	14-4	20-2	26-1	31-11	37-10
	Overall height, ft-in.	25-8	31-7	37-5	43-4	49-2
21.5 ft	Hearth area, sq ft	1077	1580	2084	2570	3046
	Column height, ft-in.	8-0	8-0	8-0	8-0	8-0
	Shell height, ft-in.	16-1	22-9	29-6	36-2	42-11
	Overall height, ft-in.	27-9	34-6	41-2	47-11	54-7

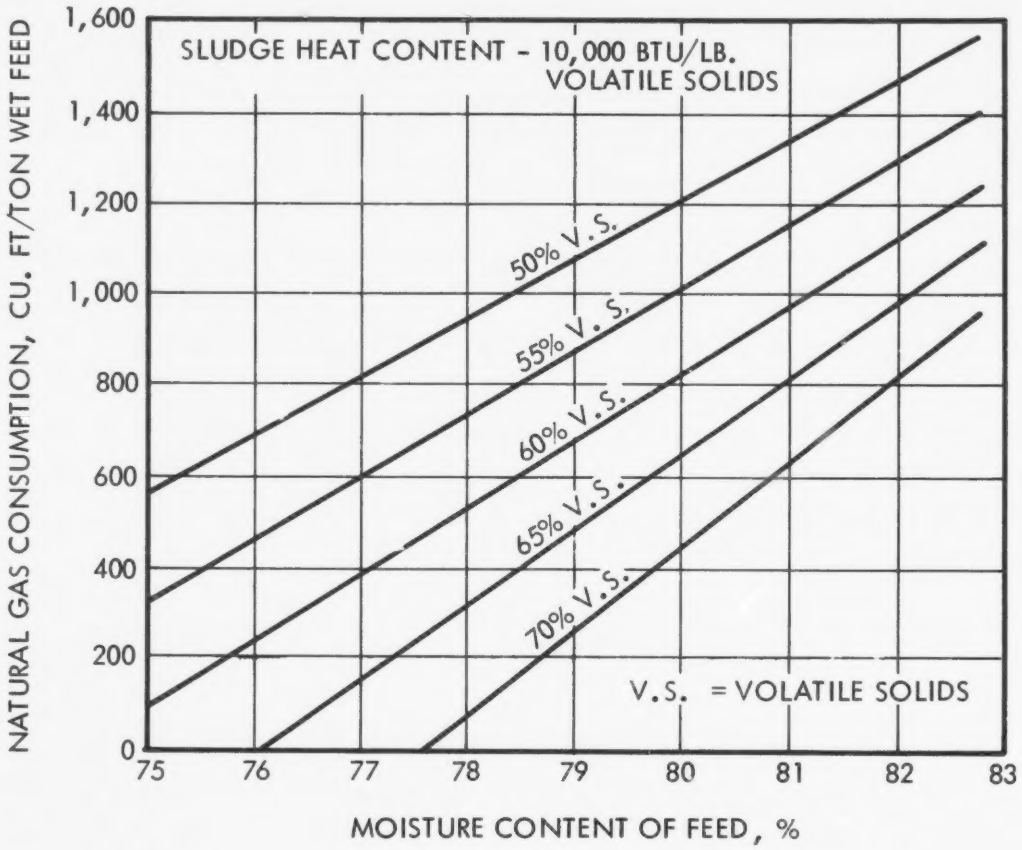


Figure 27. Fuel Requirement Variation with Feed Moisture[1761]

Process Economics. Capital and operating costs for multiple hearth incinerators will vary significantly depending upon the type and quantity of waste being incinerated, the sophistication of water and air correction equipment, waste pretreatment requirements, materials of construction, secondary fuel requirements, and labor. Total disposal cost per ton of dry solids fed are reported to range between \$8 and \$15 while operating costs generally run between \$0.50 and \$5.00 per ton of dry solids (Table 16) depending on the size of the unit.

Process Applicability. The multiple hearth incinerator is generally applicable to the ultimate disposal of most forms of combustible wastes and represents proven technology. It can incinerate combustible sludges, tars, granulated solids, liquids and gases and is especially well suited to the disposal of spent biological treatment facility sludges. For that reason, it is very likely that a National Disposal Site, especially one which contained biological treatment facilities, would contain a multiple hearth unit.

Flares[0285]

The flare type burner has been utilized in many petroleum refineries and petrochemical plants to incinerate relatively large volumes of combustible gases and aerosols. Flare burners are of two basic types: the ground flare and the elevated or tower flare. The ground flare, as its name implies, is used at ground level where there is sufficient space around the flare for safety purposes to burn waste gas from an oil field operation or similar source. The tower flare, usually found in refineries, is elevated to keep the flame well above the level of surrounding process equipment protecting the refinery against possible fires. Flares are basically open pipes which discharge a combustible gas directly to atmosphere with the end of the pipe containing a flame device and a continuous pilot or pilots to ignite the waste gas. Air for combustion is supplied by the surrounding atmosphere. Steam injection is often supplied to the flame of the flare to prevent smoking when

TABLE 16

MULTIPLE HEARTH INCINERATION COSTS[1761]

Sludge incinerated, tons/wk. (wet basis)	28.0	56.0	139.0	278.0	2,780.0
Sludge incinerated tons/wk. (dry basis)	7.0	14.0	34.75	69.5	695.0
Operating schedule, hr/wk.	35	35	70	70	168
Furnace feed, lb/hr	1,600	3,200	3,960	7,920	33,000
Furnace required	10 ft-9 in. OD 5 Hearth	14 ft-3 in. OD 5 Hearth	14 ft-3 in. OD 6 Hearth	18 ft-9 in. OD 6 Hearth	Two-22 ft-3 in. OD 8 Hearth
Installed Cost, $	120,000.00	185,000.00	200,000.00	310,000.00	750,000.00
Weekly fuel cost, $	27.50	45.00	30.00	45.00	50.00
Weekly power cost, $	9.00	12.00	13.00	25.00	165.00
Total utility cost, $	36.50	57.00	43.00	70.00	215.00
Operating cost-$/ton dry solids	5.20	4.06	1.24	1.01	0.31
Filtration cost-$/ton dry solids	8.00	8.00	8.00	8.00	8.00
Maintenance cost-$/ton dry solids	.70	.60	.60	.50	.40
Total disposal cost-$/ton dry solids	13.90	12.66	9.84	9.51	8.71

Cake moisture	75%
Volatile content	65%, 10,000 Btu/lb volatile solids
Solids removal	90%

burning waste hydrocarbon gases which have more than two carbon atoms. Flares are affected by atmospheric conditions, especially high winds. They cannot be considered an infallible method of waste gas disposal because unburned waste gases often escape from a flare system, but they are expedient and economical for high-volume discharges of combustible waste gases.

Operation Principle.[0862,1456,1460] From a pollution viewpoint, the ideal flare is a combustion device that burns waste gases completely and smokelessly. But, in actual practice, flare utilization introduces the possibility of smoke and other objectionable gases such as carbon monoxide, sulfur dioxide, and nitrogen oxides. Some types of flares have been developed that ensure that combustion is smokeless and in some cases nonluminous. Luminosity, while not an air pollution problem, does attract attention to the operation and in certain cases can cause bad public relations. There is also the consideration of military security which nonluminous emergency gas flares would be desirable.

Smoke, when present, is the result of incomplete combustion. Smokeless combustion can be achieved by: (1) adequate heat values to obtain the minimum theoretical combustion temperatures, (2) adequate combustion air, and (3) adequate mixing of the air and fuel. An insufficient supply of air results in a smoky flame. Combustion begins around the periphery of the gas stream where the air and fuel mix, and within this flame envelope the supply of air is limited. Hydrocarbon side reactions occur with the production of smoke. In this reducing atmosphere, hydrocarbons crack to elemental hydrogen and carbon, or polymerize to form hydrocarbons. Since the carbon particles are difficult to burn, large volumes of carbon particles appear as smoke upon cooling. Side reactions become more pronounced as molecular weight and unsaturation of the fuel gas increase. Olefins, diolefins, and aromatics characteristically burn with smoky, sooty flames as compared with paraffins and naphthenes. A smokeless flame can be obtained when an adequate amount of combustion air is mixed sufficiently with the fuel so that it burns completely and rapidly before any side reactions can take place. This rapid burning may be achieved by providing adequate mixing of fuel and air by means of jets. Air jets would be ideal, but the cost of providing high pressure air is prohibitive. Steam jets are the most satisfactory method of inspirating air into the combustion zone while giving good turbulence at the same time.

Steam also provides some fringe benefits: it reacts with the hydrocarbons, forming oxygenated compounds that burn readily at low temperatures, and it lowers the partial pressure of the fuel causing greater separation of the molecules. This inhibits polymerization, one of the mechanisms likely to cause smoke. The ratio of steam to hydrocarbon is important. The required ratio for smokeless operation increases with increased molecular weight and fraction of unsaturates in the waste gas.

Incineration of hydrocarbons in a typical steam-in-spirated-type elevated flare results in incomplete combustion of the feed gases. The results of a field test on a flare unit were reported in the form of ratios as follows:

CO_2: hydrocarbons	2,100:1
CO_2: CO	243:1

These results indicate that the hydrocarbons and carbon monoxide emissions from a flare can be much greater than those from properly operated boilers or furnaces.

Other contaminants that can be emitted from flares depend upon the composition of the gases burned. The most commonly detected emission is sulfur dioxide, resulting from the combustion of various sulfur compounds (usually hydrogen sulfide) in the flared gas. Toxicity, combined with low odor threshold, make venting of hydrogen sulfide to a flare an unsuitable and sometimes dangerous method of disposal. Materials that tend to cause health hazards or nuisances should not be disposed of in flares. Compounds such as mercaptans or chlorinated hydrocarbons require special combustion devices with chemical treatment of the gas or its products of combustion.

Process Design. There are, in general, two types of flares for the disposal of waste gases: elevated flares and ground-level flares. The essential parts of a flare are the burner, stack, seal, liquid trap, controls, pilot burner, and ignition system.

Smokeless combustion may be attained through the use of elevated stack flares which utilize steam injection to provide turbulence and inspirate air. Three main types of steam-injected elevated flares are in use. These types vary in the manner in which the steam is injected into the combustion zone.

In the first type, there is a commercially available multiple nozzle which consists of an alloy steel tip mounted on the top of an elevated stack (Figure 28). Steam injection is accomplished by several small jets placed concentrically around the flare tip. These jets are installed at an angle, causing the steam to discharge in a converging pattern immediately above the flare tip.

A typical refinery waste gas flare system utilizing a multiple steam jet burner is presented (Figure 29). All relief headers from process units combine into a common header that conducts the hydrocarbon gases and vapors to a large knockout drum. Any entrained liquid is dropped out and pumped to storage. The gases then flow in one of two ways. For emergency gas releases that are smaller than or equal to the design rate, the flow is directed to the main flare stack. Hydrocarbons are ignited by continuous pilot burners, and steam is injected by means of small jet fingers placed concentrically about the stack tip. The steam is injected in proportion to the gas flow. The steam control system consists of a pressure controller, having a range of 0 to 20 inches water column, that senses the pressure in the vent line and sends an air signal to a control valve in the steam line. If the emergency gas flow exceeds the designed capacity of the main flare, backpressure in the vent line increases, displacing the water seal and permitting gas flow to the auxiliary flare. Steam consumption of the burner at a peak flow is about 0.2 to 0.5 lb of steam per lb of gas, depending upon

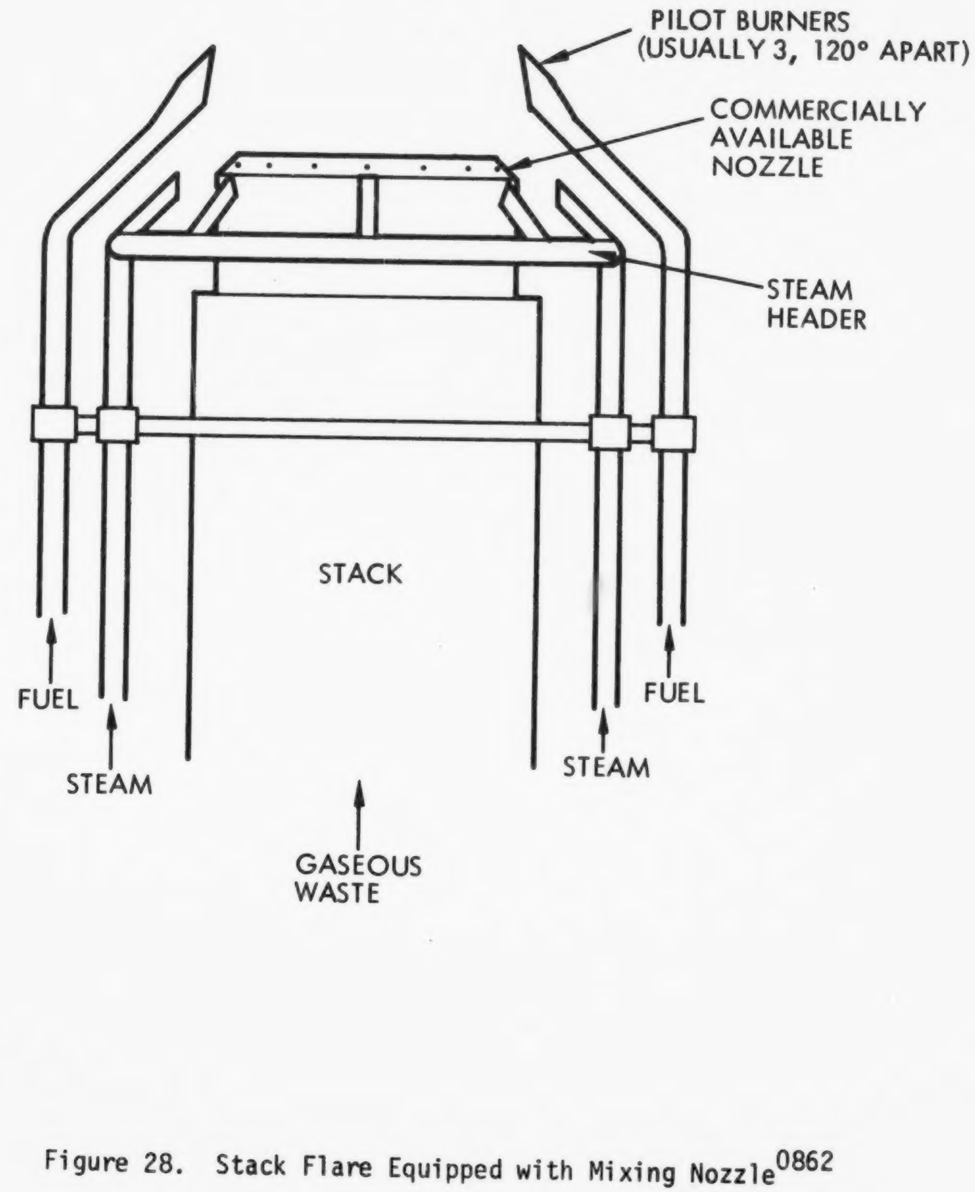

PILOT BURNERS
(USUALLY 3, 120° APART)
COMMERCIALLY
AVAILABLE
NOZZLE
STEAM
HEADER
STACK
FUEL
STEAM
FUEL
STEAM
GASEOUS
WASTE

Figure 28. Stack Flare Equipped with Mixing Nozzle[0862]

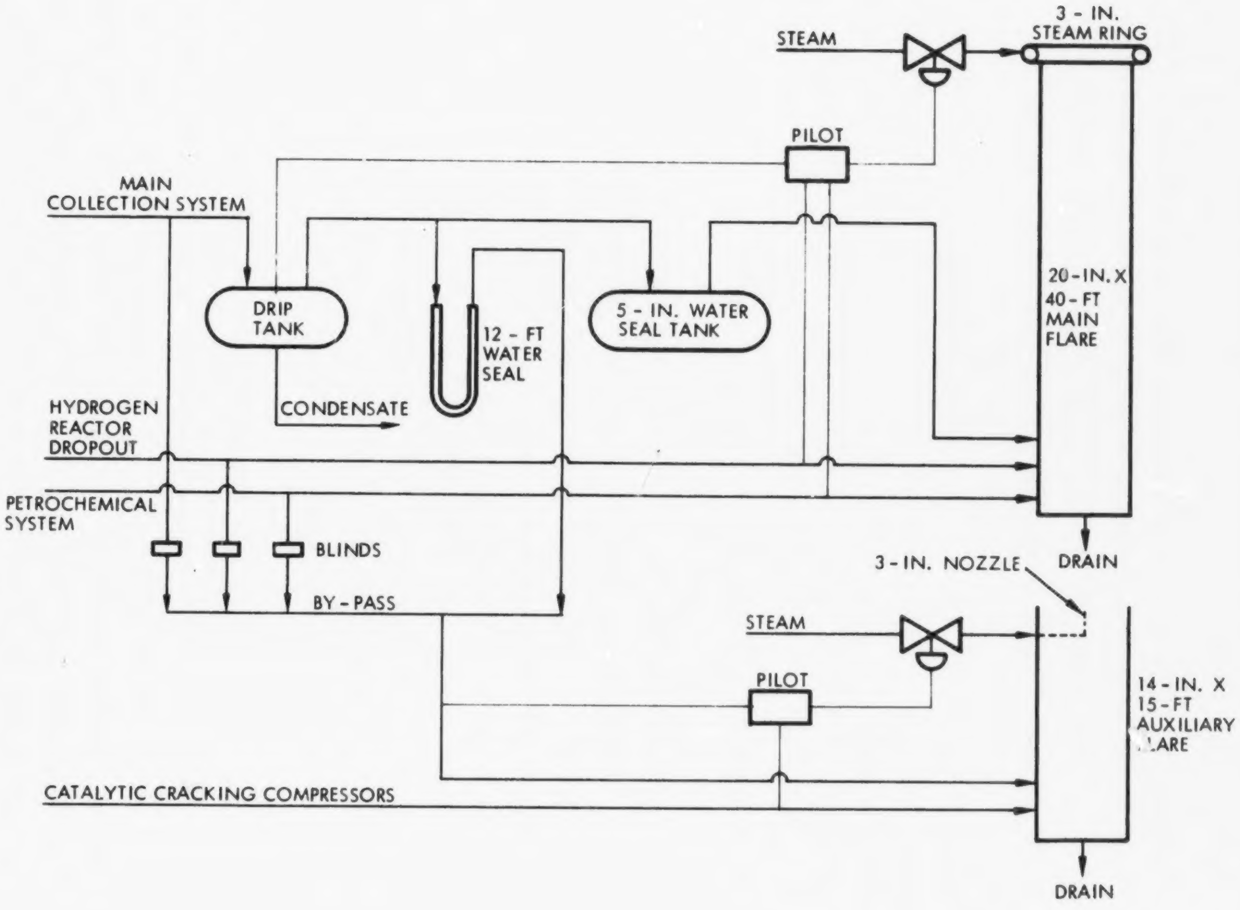

STEAM
3 - IN.
STEAM RING
PILOT
MAIN
COLLECTION SYSTEM
DRIP
TANK
12 - FT
WATER
SEAL
5 - IN. WATER
SEAL TANK
20-IN. X
40-FT
MAIN
FLARE
CONDENSATE
HYDROGEN
REACTOR
DROPOUT
PETROCHEMICAL
SYSTEM
BLINDS
BY-PASS
DRAIN
3-IN. NOZZLE
STEAM
PILOT
14-IN. X
15-FT
AUXILIARY
FLARE
CATALYTIC CRACKING COMPRESSORS
DRAIN

Figure 29. Waste Gas Flare System Using a Multiple Steam Jet Burner

the amount and composition of hydrocarbon gases being vented.

A small amount of steam (300 to 400 lb per hour) is allowed to flow through the jet fingers at all times. This steam not only permits smokeless combustion of gas flows too small to actuate the steam control valves but also keeps the jet fingers cooled and open.

A second type of elevated flare has a flare tip with no obstruction to flow, that is, the flare tip is the same diameter as the stack. The steam is injected by a single nozzle located concentrically within the burner tip. In this type of flare, the steam is premixed with the gas before ignition and discharge. This configuration flare is generally referred to as an Esso type flare (Figure 30).

A typical flare system serving a petrochemical plant using this type burner is shown (Figure 31). The type of hydrocarbon gases vented can range from a saturated to a completely unsaturated material. The injection of steam is not only proportioned by the pressure in the blowdown lines but is also regulated according to the type of material being flared. This is accomplished by the use of a ratio relay that is manually controlled. The relay is located in a central control room where the operator has an unobstructed view of the flare tip. In normal operation the relay is set to handle feed gas which is most common to this installation.

In this installation, a blowdown header conducts the gases to a water seal drum and the end of the blowdown line is equipped with two slotted orifices. The flow transmitter senses the pressure differential across the seal drum and transmits an air signal to the ratio relay. The signal to this relay is either amplified or attenuated, depending upon its setting. An air signal is then transmitted to a flow controller that operates two parallel steam valves. The 1-inch steam valve begins to open at an air pressure of 3 psig and is fully open at 5 psig. The 3-inch valve starts to open at 5 psig and is fully open at 15 psig air pressure. As the gas flow increases, the water level in the pipe becomes lower than the water level in the drum, and more of the slot is uncovered. Thus,

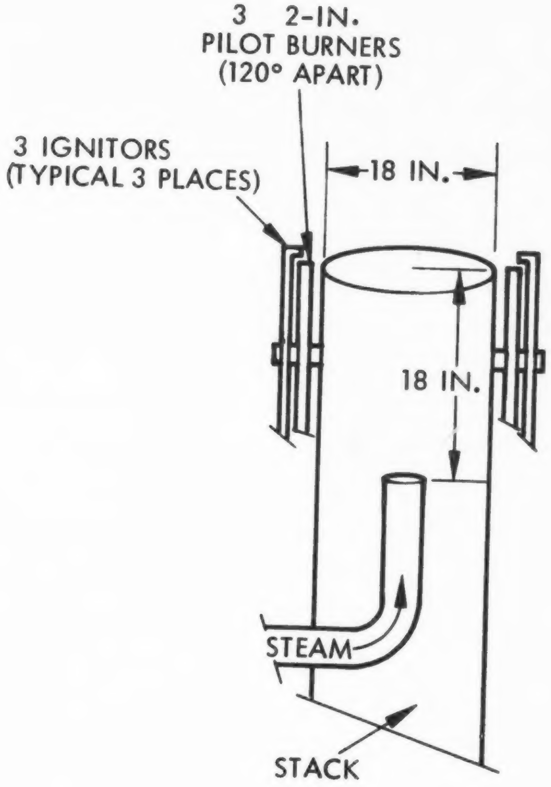

3 2-IN.
PILOT BURNERS
(120° APART)
3 IGNITORS
(TYPICAL 3 PLACES)
18 IN.
18 IN.
STEAM
STACK

Figure 30. Esso Type Flare[0862]

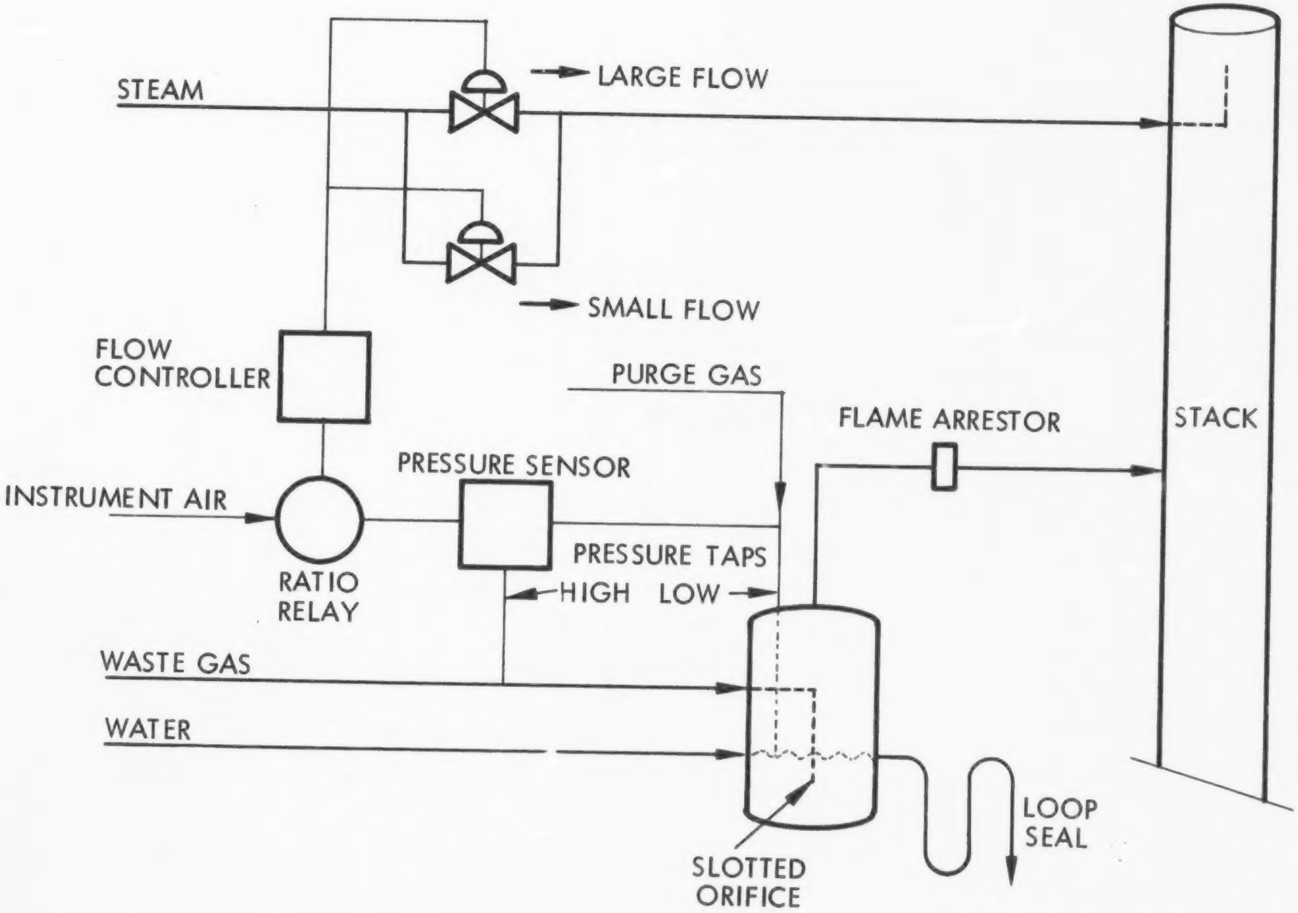

STEAM
LARGE FLOW
SMALL FLOW
FLOW CONTROLLER
PURGE GAS
FLAME ARRESTOR
STACK
PRESSURE SENSOR
INSTRUMENT AIR
PRESSURE TAPS
HIGH
LOW
RATIO RELAY
WASTE GAS
WATER
LOOP SEAL
SLOTTED ORIFICE

Figure 31. Waste-Gas Flare System Using Esso Type Burner[0862]

the difference in pressure between the line and the seal drum increases. This information is transmitted as an air signal to actuate the steam valves. The slotted orifice senses flows that are too small to be indicated by a pitot-tube-type flow meter. The water level is maintained 1-1/2 inches above the top of the orifice to take care of sudden surges of gas to the sytem.

A 3-inch steam nozzle is so positioned within the stack so that the expansion of the steam just fills the stack and mixes with the gas to provide smokeless combustion. This type of flare is probably less efficient in the use of steam than some of the commercially available flares but is desirable from the standpoints of simpler construction and lower maintenance costs.

A third type of flare, the Sinclair elevated flare (Figure 32) is equipped with a flare tip constructed to cause the gases to flow through several tangential openings to promote turbulence. A steam ring at the top of the stack has numerous equally spaced holes about 1/8 inch in diameter for discharging steam into the gas stream.

The injection of steam in this latter flare may be automatically or manually controlled. In most cases, the steam is proportioned automatically to the rate of gas flow: however, in some installations, the steam is automatically supplied at maximum rates, and manual throttling of a steam valve is required for adjusting the steam flow to the particular gas flow rate. There are many variations of instrumentation among various flares, some designs being more desirable than others. For economic reasons, all designs attempt to proportion steam flow to the gas flow rate.

There are four principal types of ground level flare: horizontal venturi, water injection, multijet, and vertical venturi. A typical horizontal venturi-type ground flare system is shown (Figure 33).

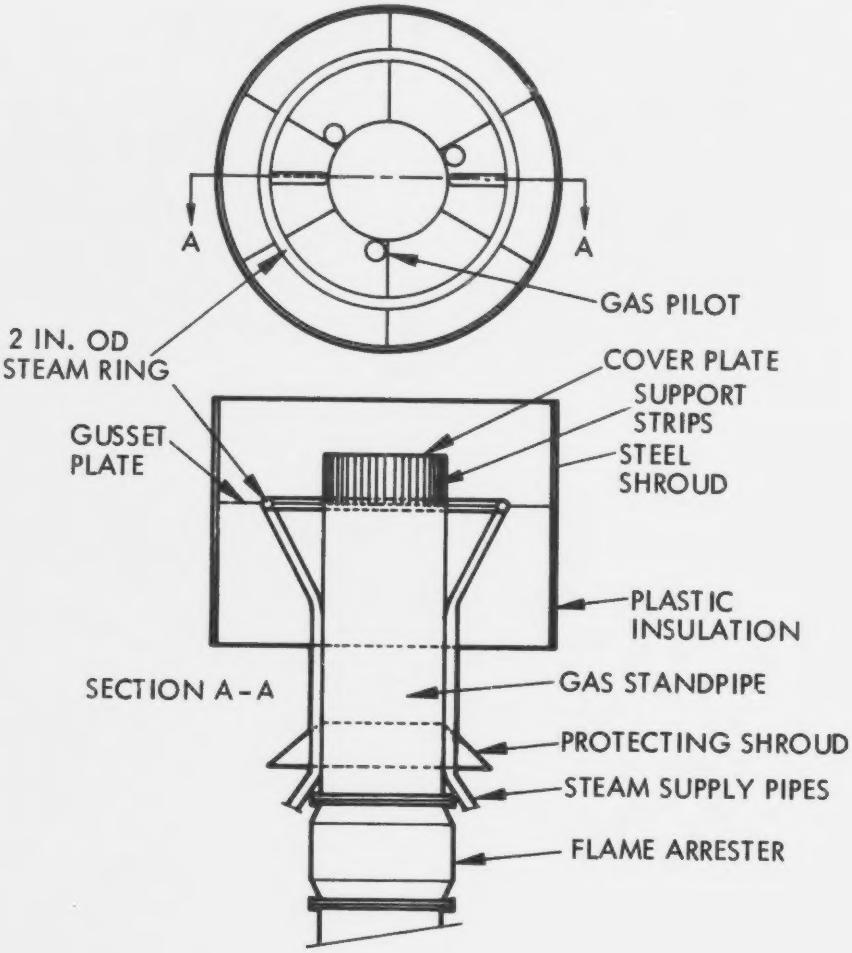

A
A
GAS PILOT
2 IN. OD
STEAM RING
COVER PLATE
SUPPORT
STRIPS
GUSSET
PLATE
STEEL
SHROUD
PLASTIC
INSULATION
SECTION A-A
GAS STANDPIPE
PROTECTING SHROUD
STEAM SUPPLY PIPES
FLAME ARRESTER

Figure 32. Sinclair Type Flare[0862]

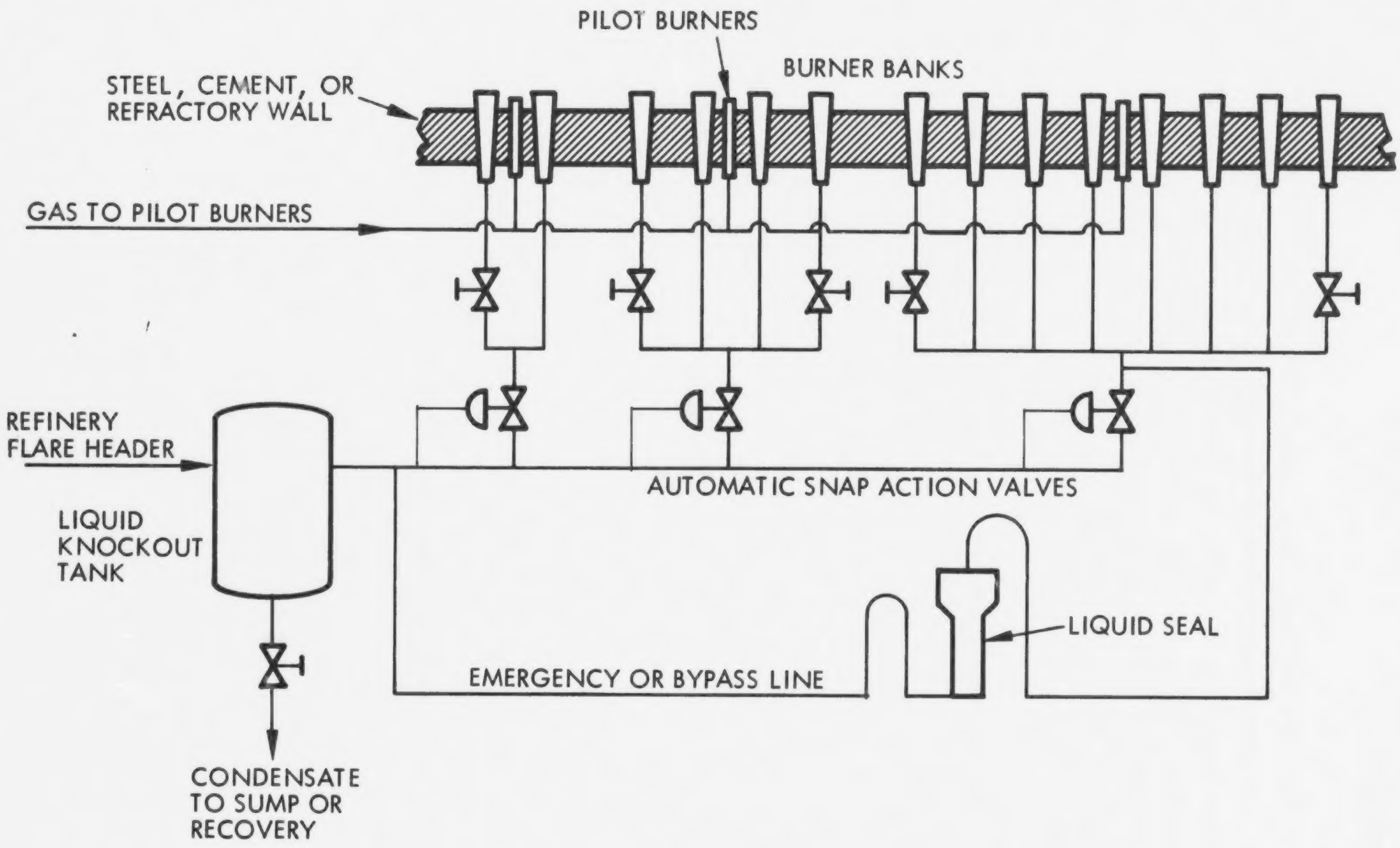

PILOT BURNERS
BURNER BANKS
STEEL, CEMENT, OR REFRACTORY WALL
GAS TO PILOT BURNERS
REFINERY FLARE HEADER
LIQUID KNOCKOUT TANK
AUTOMATIC SNAP ACTION VALVES
LIQUID SEAL
EMERGENCY OR BYPASS LINE
CONDENSATE TO SUMP OR RECOVERY

Figure 33. Typical Venturi Ground Flare[0862]

In this system, the refinery flare header discharges to a knockout drum where any entrained liquid is separated and pumped to storage. The gas flows to the burner header, which is connected to three separate banks of standard gas burners through automatic valves of the snap-action type that open at predetermined pressures. If any or all of the pressure valves fail, a bypass line with a liquid seal is provided (with no valves in the circuit), which discharges to the largest bank of burners.

Another type of ground flare used in petroleum refineries has a water spray to inspirate air and provide water vapor for the smokeless combustion of gases (Figure 34). This flare requires an adequate supply of water (Table 17) and a reasonable amount of open space.

The structure of the flare consists of three concentric stacks. The combustion chamber contains the burner, the pilot burner, the end of the ignitor tube, and the water spray distributor ring. The primary purpose of the intermediate stack is to confine the water spray so that it will be mixed intimately with burning gases. The outer stack confines the flame and directs it upward.

Water is not as effective as steam for controlling smoke with high gas flow rates, unsaturated materials, or wet gases. The water spray flare is economical when venting rates are not too high and slight smoking can be tolerated.

A recent type of flare developed by the refining industry is known as a multijet . This type of flare was designed to burn excess hydrocarbons without smoke, noise, or visible flame.

A sketch of a multijet flare installation is shown (Figure 35). The flare uses two sets of burners; the smaller group handles normal gas leakage and small gas releases, while both burner groups are used at higher flaring rates. This sequential operation is controlled by two water-sealed drums set to release at different pressures. In extreme emergencies, the multijet burners are by-passed by means of a water

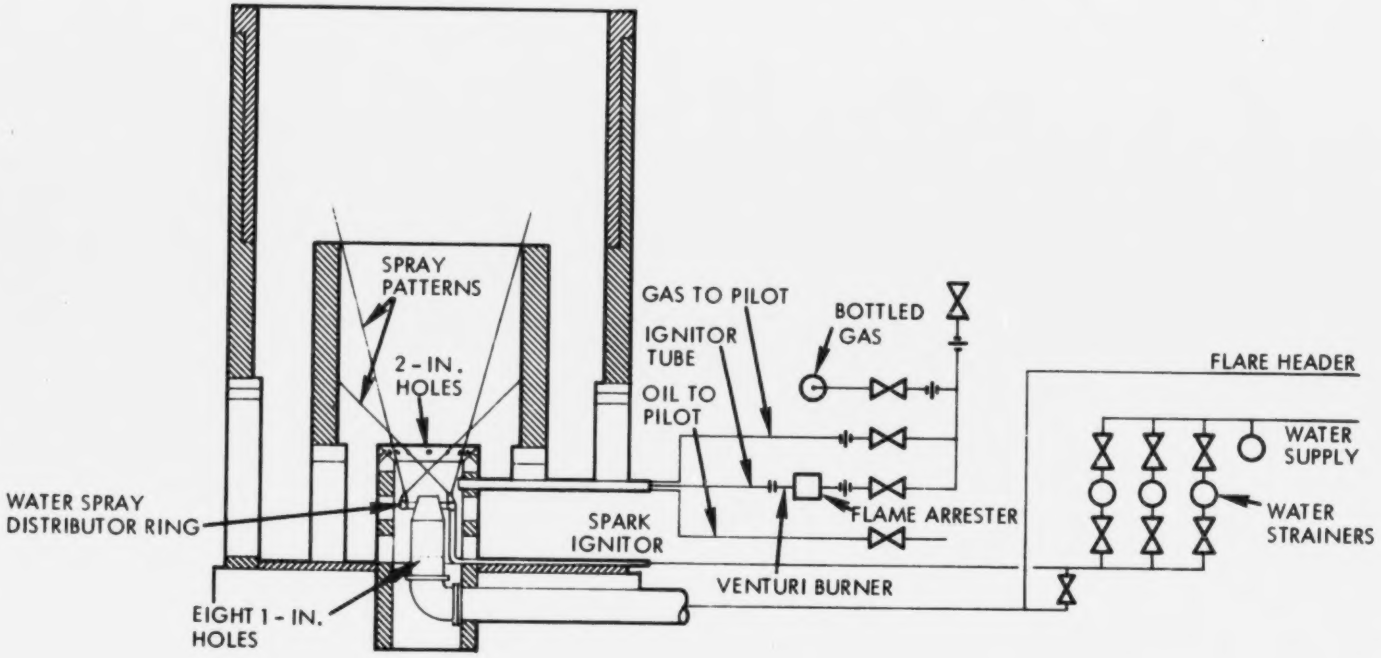

SPRAY PATTERNS
2-IN. HOLES
WATER SPRAY DISTRIBUTOR RING
EIGHT 1-IN. HOLES
SPARK IGNITOR
GAS TO PILOT
IGNITOR TUBE
OIL TO PILOT
BOTTLED GAS
FLAME ARRESTER
VENTURI BURNER
FLARE HEADER
WATER SUPPLY
WATER STRAINERS

Figure 34. Typical Water Spray Type Ground Flare[0862]

TABLE 17

WATER SPRAY PRESSURES REQUIRED FOR SMOKELESS BURNING*[0862]

Gas rate, scfh	Unsaturates, % by vol	Molecular weight	Water pressure, psig	Water rate, gpm
200,000	0 to 20	28	30 to 40	31 to 35
150,000	30	33	80	45
125,000	40	37	120	51

* The data in this table were obtained with a 1-1/2 inch-diameter spray nozzle in a ground flare with the following dimensions:

	Height, ft	Diameter, ft
Outer stack	30	14
Intermediate stack	12	6
Inner stack	4	2.5

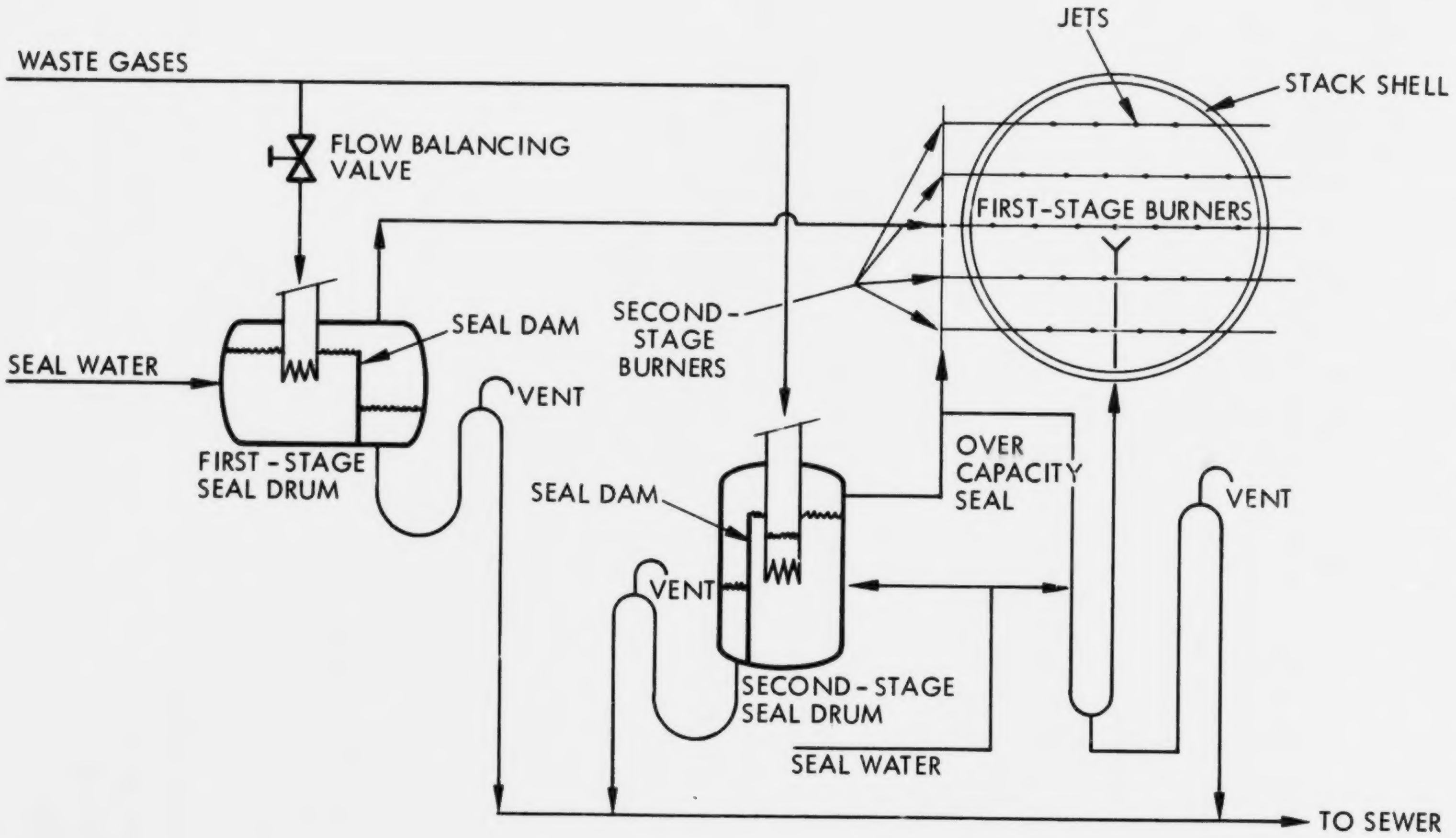

JETS
WASTE GASES
STACK SHELL
FLOW BALANCING VALVE
FIRST-STAGE BURNERS
SECOND-STAGE BURNERS
SEAL DAM
SEAL WATER
VENT
FIRST-STAGE SEAL DRUM
OVER CAPACITY SEAL
SEAL DAM
VENT
VENT
SECOND-STAGE SEAL DRUM
SEAL WATER
TO SEWER

Figure 35. Multiject Flare System[0862]

seal that directs the gases to the center of the stack. This seal blows at flaring rates higher than the design capacity of the flare. At such an excessive rate, the combustion is both luminous and smoky, but the unit is usually sized so that an overcapacity flow would be a rare occurrence. The overcapacity line may also be designed to discharge through a water seal to a nearby elevated flare rather than to the center of a multijet stack. Similar staging could be accomplished with automatic valves or backpressure regulators; however, in this case, the water seal drums are used because of reliability and ease of maintenance. The staging system is balanced by adjusting the hand control butterfly valve leading to the first-stage drum. After its initial setting, this valve is locked into position.

The fourth type of flare,based upon the use of commercial-type venturi burners,is presented (Figure 36). This type of flare has been used to handle vapors from gas-blanketed tanks, and vapors displaced from the depressuring of butane and propane tank trucks. Since the commercial venturi burner requires a certain minimum pressure to operate efficiently, a gas blower must be provided. Generally, burners operate at a pressure of 1/2 to 8 psig.

This type of flare is suitable for relatively small flows of gas of a constant rate (Table 18). Its main application is in situations where other means of disposing of gases and vapors are not available.

Most refineries and petrochemical plants have a fixed schedule for inspection and maintenance of processing units and their auxiliaries. The flare system should not be exempted from this practice. Removal of a flare from service for maintenance requires some type of standby equipment to disperse emergency gas vents during the shutdown. A simple stack with pilot burner should suffice for a standby. Coordinating this inspection to take place at the time when the major processing units are also shut down is good practice.

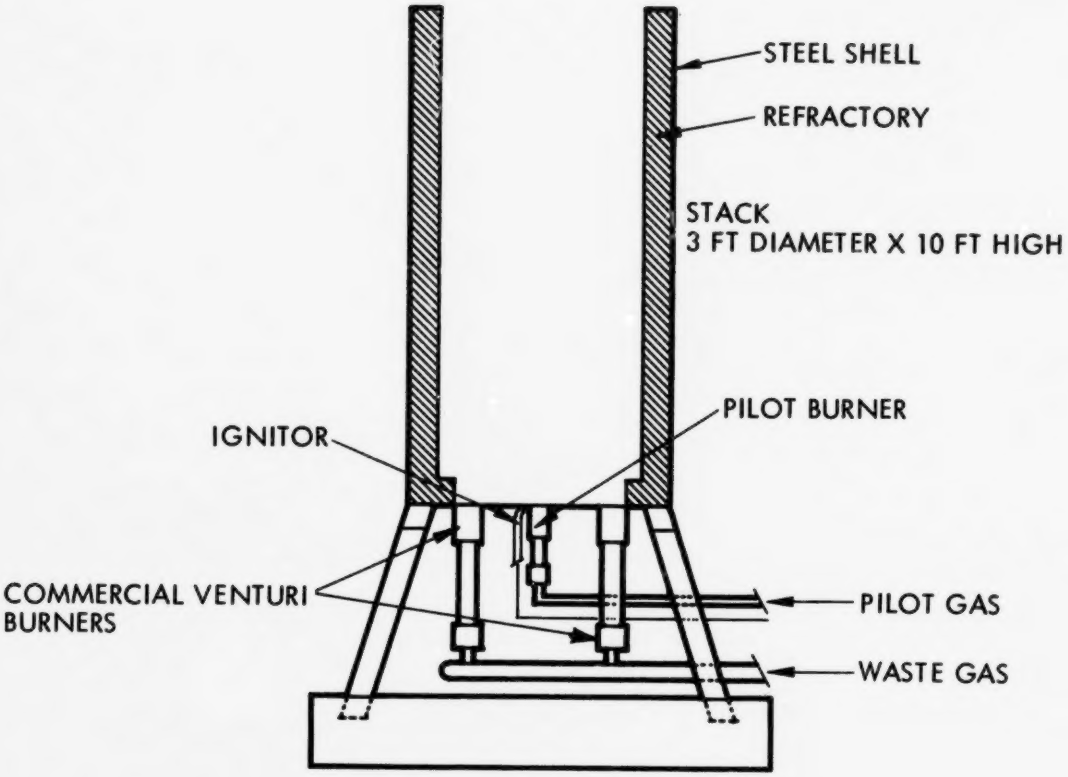

STEEL SHELL
REFRACTORY
STACK
3 FT DIAMETER X 10 FT HIGH
PILOT BURNER
IGNITOR
COMMERCIAL VENTURI BURNERS
PILOT GAS
WASTE GAS

Figure 36. Vertical Venturi Type Flare[0862]

TABLE 18

VENTURI BURNER CAPACITIES, FT^3/HR^{0862}

Gas pressure, in. H_2O	3/16-in. orifice	7/16-in. orifice	1/2-in. orifice
2	70		
4	100		
6	123		
8	142		
10	160		
1/2 psig	210	1,042	1,360
1 psig	273	1,488	1,900
2 psig	385	2,157	2,640
3 psig		2,654	3,200
4 psig		3,065	3,680
5 psig		3,407	4,080
6 psig		3,742	4,480
7 psig		4,040	4,800
8 psig		4,320	5,160

Basis: 1,000 Btu/ft^3 natural gas.

Flare instrumentation requires scheduled maintenance to ensure proper operation. Most of the costs and problems of flare maintenance arise from this instrumentation. Maintenance expenses for flare burners can be reduced by constructing them of chrome-nickel alloy. Because of the inaccessibility of elevated flares, the use of alloy construction is recommended.

Process Economics.[0862,1456,1460,1533] Capital and operating costs for flare installations are scarce. The capital investment will vary significantly depending upon the complexity of the overall system, the type and quantity of waste gas being combusted and the materials of construction. Capital costs of flare systems have been reported to range from $1 to $100 per 1,000 SCFH of capacity. Operating costs are mainly a function of steam, water and pilot fuel requirements, maintenance and labor.

Process Applicability. Flares are generally applicable to the ultimate disposal of large volumes of combustible gases and aerosols. They have found application in most petroleum refineries and petrochemical plants. However, flares are not recommended for use at National Disposal Sites because of the associated lack of effluent control. This lack of control might result in emissions to the surroundings of harmful conbustion products such as chlorides, fluorides, cyanides, sulfur compounds, carbon monoxide and any partially combusted or uncombusted waste material.

Additionally, the form of waste handled by industrial flares (concentrated gases in large volumes) suggests that flares are best suited for use at the processing sites where the waste gas is generated.

Gas Combustors[1533,1534]

Gas combustors, or as they are more commonly called, direct-flame thermal incinerators, are utilized to dispose of low concentration (usually less than 25 percent of the lower flammability limit) combustible gaseous waste. They have found wide application in the chemical and food processing industries.

In direct-flame incineration combustible emissions are destroyed by exposure,under the proper conditions, to temperatures of 900 to 1,500 F. in the presence of a flame. The actual temperature required to do an effective job depends on the specific pollutants involved and the design of the combustion chamber.

Operation Principle.[0862,1533,1534] The basic components of a direct-flame thermal incinerator are presented schematically (Figure 37). They are the combustion chamber, gas burner, burner controls, and temperature indicator. Operation of the unit is relatively simple. The contaminated gases are delivered to the combustor from the process equipment by an exhaust system. The combustion chamber must be designed for complete mixing of the contaminated gases with the flames and burner combustion gases. The presence of a flame is important for contaminant removal. Evidence indicates that when using electric heat energy, much higher temperatures are required--1,500 to 1,800 F--to obtain the same efficiency achieved with a direct-flame system at 1,000 to 1,400 F. One satisfactory method of achieving proper mixing is the admission of the contaminated gases into a throat where the burner is located. Sufficiently high velocities may be obtained here for thorough mixing of the gases with the burner combustion products in the region of highest temperature.

Next, the gases pass into the main section of the combustor where velocity is reduced somewhat by the larger cross-sectional area. Here the combustion reactions are completed and the incinerated air contaminants and combustion gases are discharged to either heat recovery equipment, scrubbers or directly to the stack.

Direct-flame incineration can be highly effective. Experience has shown that direct-flame incineration systems can operate continuosuly at efficiencies of 90 to 99+ percent. Such systems can be readily adapted for automatic temperature control. This is an important consideration in processes where 100 percent continuous pollution abatement is required in spite of changing conditions. Temperature control can be obtained through the

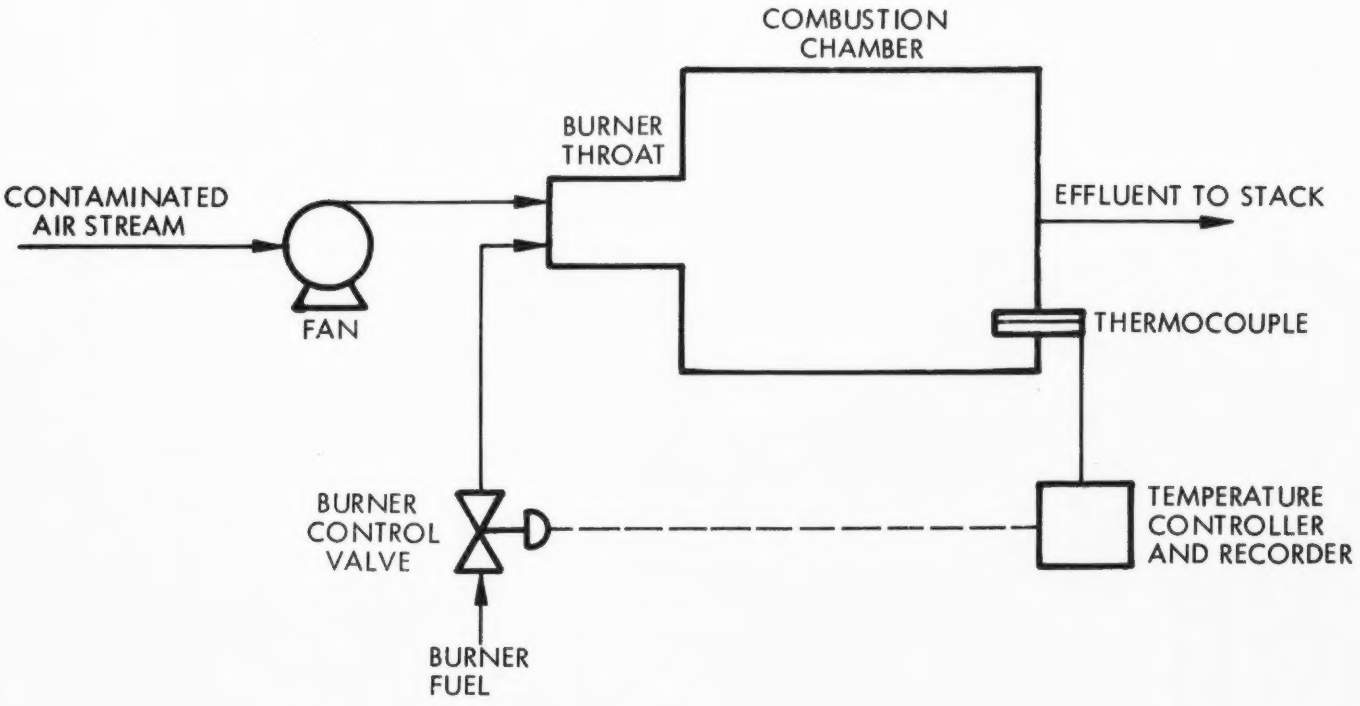

COMBUSTION CHAMBER
BURNER THROAT
CONTAMINATED AIR STREAM
FAN
EFFLUENT TO STACK
THERMOCOUPLE
BURNER CONTROL VALVE
TEMPERATURE CONTROLLER AND RECORDER
BURNER FUEL

Figure 37. Direct-Flame Thermal Incinerator[0862]

installation of modulating gas burner controls. These controls may effect considerable savings in fuel where the volume of gases or the amount of combustible material delivered to the combustor varies appreciably during the process cycle, or where both vary. A constant temperature in the afterburner chamber can be maintained through a gas temperature sensing element that actuates the burner input control. When, however, the volume of contaminated gases and the amount of combustible materials remain relatively constant, the firing of the burner at a fixed rate is preferable.

An indicating--or recording-type temperature-measuring device is usually installed to show the combustors operating temperature at all times. A bare thermocouple is normally used because of low cost and rapid response to temperature changes. The thermocouple should be located near the end of the combustion chamber to avoid large errors produced by direct radiations from the burner flames. The thermocouples may be installed in a thermocouple well for protection.

A safety pilot is usually provided to shut off the burner gas supply if the main burner malfunctions or the flow of contaminated gases to the combustor is interrupted. It may also be advisable to install a high-temperature-limiting control to shutoff the gas burner fuel supply when combustion temperatures exceed safe operating levels.

Process Design.[0862,1533,1534,1792] In order to properly design an effective direct-flame fume incineration system, the following information is required: flow to be handled (scfm); temperature and pressure of gases to be handled; list of contaminants involved--type and concentration; deposit problem, if any; fuel available--natural gas or oil; cost of fuel; number of hours of plant operations; and an indication if heat energy can be used elsewhere in the plant.

There are basically two basic configurations of direct-flame thermal combustors; vertical and horizontal units (Figures 38 and 39). The type of unit utilized is usually dictated by heat recovery requirements. That is, vertical units are usually used when no heat recovery is desired while horizontal units are well suited for this application.

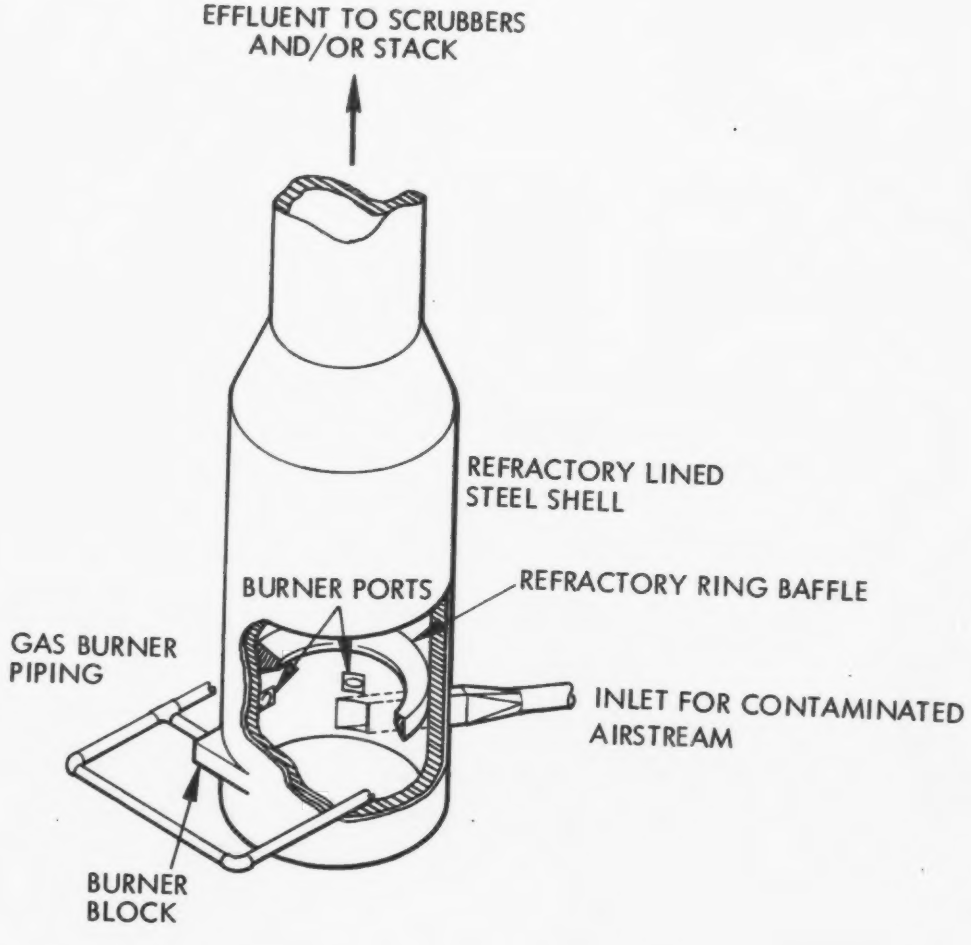

EFFLUENT TO SCRUBBERS AND/OR STACK
REFRACTORY LINED STEEL SHELL
BURNER PORTS
REFRACTORY RING BAFFLE
GAS BURNER PIPING
INLET FOR CONTAMINATED AIRSTREAM
BURNER BLOCK

Figure 38. Vertical Direct-Flame Combustor Without Heat Recovery[0862]

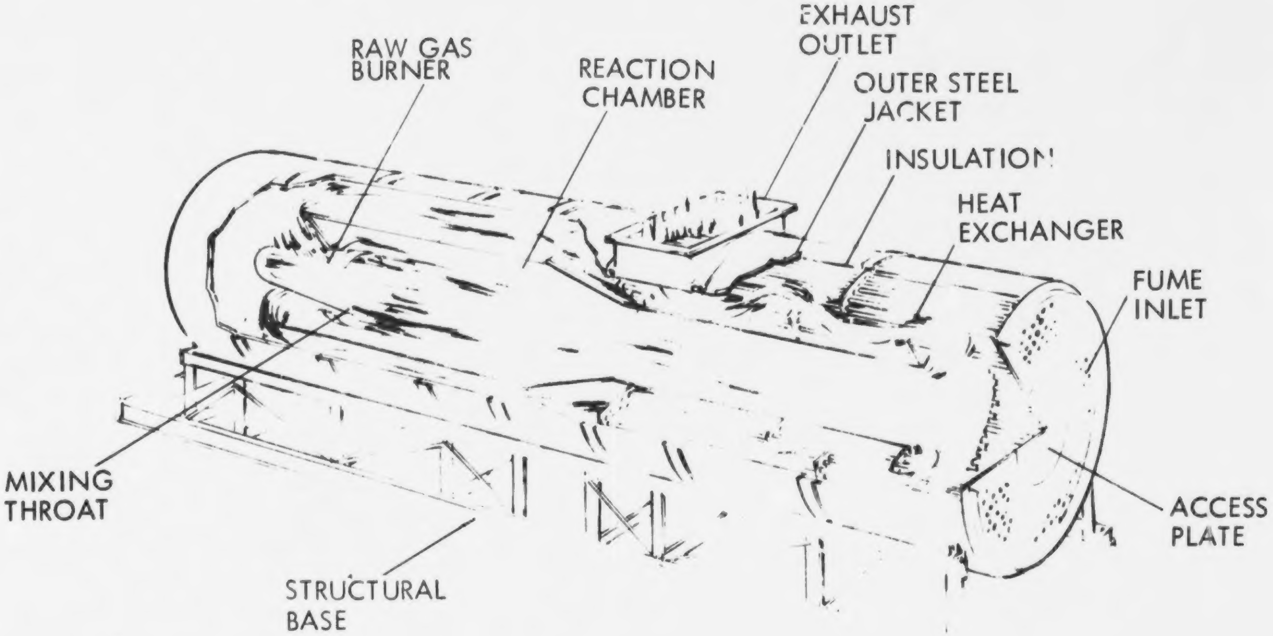

EXHAUST OUTLET
RAW GAS BURNER
REACTION CHAMBER
OUTER STEEL JACKET
INSULATION
HEAT EXCHANGER
FUME INLET
ACCESS PLATE
MIXING THROAT
STRUCTURAL BASE

Figure 39. Horizontal Direct-Flame Combustor with Heat Recovery[1792]

Direct-flame combustors, regardless of form, usually operate with throat velocities ranging from 15 to 25 fps, and combustion chamber residence times between 0.3 and 0.5 seconds. Operating temperatures are usually between 850 and 1500 F depending upon the waste being combusted. Standard industrial units are available with capacities ranging from 2,000 to 30,000 scfm of contaminated waste gas.

Most direct-flame incinerators are constructed of firebrick or castable refractory with a sheet iron shell. Several types of gas burners have been successfully utilized in direct-flame combustors. Among these are: atmospheric, nozzle mixing, pressure mixing, premixing, and multijet gas burners.

Process Economics.[0285,0862,1461,1533] The installed capital cost of a function of the difficulty of the combustion reaction, materials of construction and the extent of heat recovery operating costs generally reflect fuel consumption and are therefore dependent upon inlet gas temperatures and the required combustion temperature. They also reflect maintenance and labor. Estimates from various literature sources of both capital and operating costs are presented (Table 9).

Process Modifications.[1459,1460,1461] The primary process modifications utilized in direct-flame thermal combustion are waste heat recovery options. The principle heat recovery options are influent preheat through heat exchange with the hot gaseous effluent and effluent heat exchange with other process streams (Figure 40).

Additionally, secondary scrubbers may be utilized to further decrease concentrations of pollutants such as chlorides, fluorides, sulfur containing compounds and nitrogen oxides when they are present. This practice is usually very expensive since the contaminant levels in the combustor effluent stream are usually very low.

TABLE 19.

PROCESS ECONOMICS FOR DIRECT-FLAME INCINERATION

	Amount of Gas Treated, scfm*	Influent Gas Temp F	Capital Cost $/scfm	Annual Fuel Cost $/Year
Data from Reference No. 1533				
Basic Unit	10,000	350	2.00	48,000
		550	1.95	30,700
Basic Unit with Heat Exchanger	10,000	350	2.40	33,500
		550	2.39	12,200
Data from Reference No. 1461				
Basic Unit with Heat Exchanger	5,000	400	2.60	8,600
	25,000	150	3.20	35,400
Data from Reference No. 0285				
Basic Unit	10,000	300	1.50-2.00	†
Basic Unit with Heat Exchanger	10,000	300	3.00-4.50	†
Data from Reference No. 0862				
Basic Unit	†	†	5.00-10.00‡	†

*Contaminants are at less than 25% of L.E.L.

‡Installed capital cost

†No data available

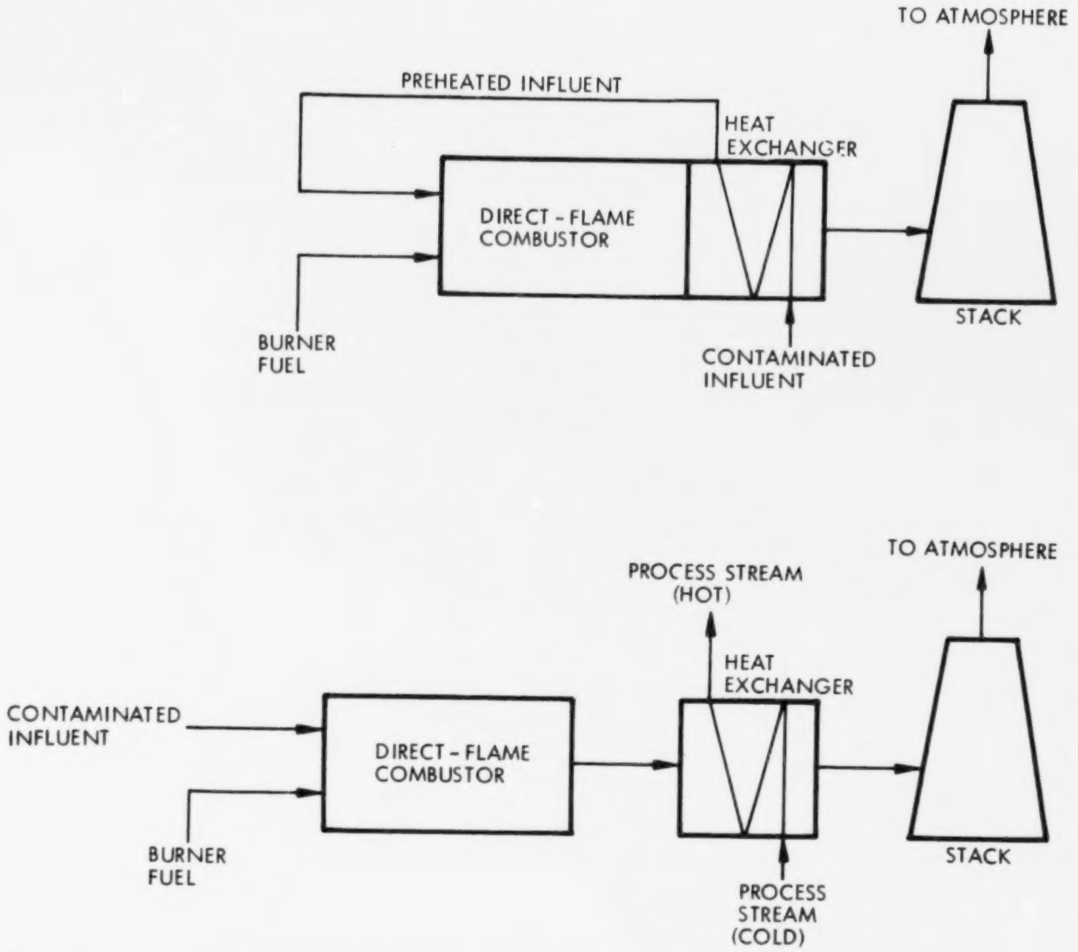

TO ATMOSPHERE
PREHEATED INFLUENT
HEAT EXCHANGER
DIRECT - FLAME COMBUSTOR
BURNER FUEL
STACK
CONTAMINATED INFLUENT
TO ATMOSPHERE
PROCESS STREAM (HOT)
HEAT EXCHANGER
CONTAMINATED INFLUENT
DIRECT - FLAME COMBUSTOR
BURNER FUEL
STACK
PROCESS STREAM (COLD)

Figure 40. Heat Recovery Options

Process Applicability. Due to the form of the waste material being treated (dilute and in the gaseous state) direct-flame combustors are best suited for use at the processing site where the waste is generated. A listing of some of the typical industrial applications of direct-flame combustion systems is presented (Table 20).[1792]

Direct-flame combustors would find use at a National Disposal Site as a secondary treatment (i.e., afterburner) on primary treatment processes evolving varying amounts of combustible contaminants. They are also well suited to the purification of ventilation air or any air which is monitored for pollutant control.

TABLE 20

TYPICAL DIRECT FLAME INCINERATION APPLICATIONS[1792]

Resin Manufacturing
Paint and Varnish Cooking
Wire Enameling
Metal Decorating
Coil and Strip Coating
Carbon Baking Ovens
Tar and Asphalt Blowing
Fish Meal Processing
Printing Press Ink Drying
Phthalic and Maleic Anhydride Manufacture
Food Processing
Rendering of Fats
Bonding and Burn-off
Grain Dryers
Plastic Curing
Sewage Treatment
Air Sterilization

APPENDIX

AIR CORRECTION EQUIPMENT

1. INTRODUCTION

The following is a discussion of the general types of air correction equipment currently employed for the control of gaseous and/or particulate pollutants in process effluent streams. There are currently two general categories of abatement equipment in use--wet collection equipment and dry collection equipment. This report will summarize the general operating principles, operational characteristics, and applications of the common types of pollution control equipment.

2. WET COLLECTION EQUIPMENT[2188,1673,2189]

In the collection of gaseous pollutants, the primary removal mechanism in wet collection systems is the absorption of the gaseous pollutant into water or other suitable solvents. The basic operation consists of the diffusion of the gas molecules to the water surface. Concentration differentials near the liquid/gas interface serve as the driving force. Control equipment which applies this principle is characterized by high interfacial surface areas, turbulence in the gas phase, and high diffusion coefficients. Fortunately, in the area of gaseous emission control, a great number of the most common gaseous chemical species have high solubility in water.

Particulate collection liquid scrubbers depend upon a somewhat different set of physical processes. The primary collection mechanism is the impaction of solid particulate material on liquid droplets generated in the scrubber. The function of the liquid scrubber is to generate and place in contact with the exhaust gas stream a sufficient number of liquid droplets in the appropriate droplet size range. Additional physical mechanisms by which particulate dispersoids are collected in wet scrubbers are Brownian diffusion, condensation of liquid on the particulate material, and agglomeration. In each case, the relative effective size of the particulate material is increased in the scrubber, thus facilitating its ultimate collection and disposal.

It should be noted that the mechanisms of gaseous and particulate collection in liquid collectors are somewhat different and that a liquid scrubber designed to maximize gaseous pollutant removal may be significantly less effective in the collection of particulate material. Application of scrubbers to specific industrial effluent cleaning tasks should be made only on the basis of careful consideration of the relative importance of the gaseous and particulate emissions and analysis of the particle size distribution in the effluent gas stream to be cleaned.

Spray Towers/Chambers

A chamber scrubber consists of a chamber into which the water or an aqueous solution is introduced through spray nozzles. The gas stream may make a single direct pass through the chamber, or the path may be controlled by a series of baffles. Several such chambers or scrubbers are often used sequentially to produce the desired degree of pollutant removal. These devices are characterized by a very low pressure drop for the gas phase (0.1 to 0.5 in. of water). Water pressure required for spray operation ranges from 20 to 100 lb per square in. Water consumption is usually in the range of 1/2 to 2 gal per 1,000 cubic feet of gas treated.[2188]

Spray chambers are used for the removal of both particulate and gaseous pollutants. The efficiencies of these devices are generally rather low for particulate materials and are suitable only for the removal of particulate materials 10 microns in size or larger. For the collection of smaller particulate material, very high water pressures have been successfully used. Water pressures on the order of 300 to 450 lb per square in. (psi) produce a fog spray which will achieve collection efficiencies of the order of 90 percent for particles in the 1 to 2 micron size range. The larger water pressure drops required to acheive high efficiency fog spray result in a proportionally higher pump horsepower and operating cost. Baffled spray chambers require higher gas velocities and result in greater gas pressure drops which, in turn, require greater fan horsepower to recover the lost pressure head and more expensive ductwork.

The simple spray chamber is often used effectively for gaseous pollution control, especially when treating some of the relatively more soluble pollutants. Surface contact area, an important consideration in gaseous absorption, is relatively low in spray chambers compared with other types of liquid scrubbers. For this reason, simple spray chambers must be very large to produce efficiencies equivalent to more sophisticated liquid collection systems. The overall efficiencies reported for multiple spray chamber installations are greater than 90 percent. There are no limitations on gas throughput volume other than those imposed by equipment size limits. However, gas flow rates of approximately 800 $lb/hr\text{-}ft^2$ have been demonstrated as the upper limit, to prevent excessive liquid entrainment.[1673]

Spray chambers or towers, because of their simple design, represent one of the most economical control devices to purchase and install. The operating and maintenance expenses associated with this type of device are also low because of the mechanical simplicity. Primary maintenance problems are caused by the use of small, high-pressure nozzles which may tend to clog under prolonged usage. The low pressure drops (generally less than 1 in. of water) allow the use of inexpensive ductwork and fans to convey the effluent gas stream to the collector.

Packed Bed Scrubbers

The packed bed scrubber is similar to the spray chamber described above in that the effluent gas stream to be cleaned is directed through a chamber or tower in which it makes contact with the scrubbing liquid. The high liquid surface area exposed to the gas stream is produced by interaction with the packed bed. The packed bed may be in the form of a fixed packing or loose material which is supported by the action of the gas stream passing through it. This latter type is called a floating bed scrubber. Scrubbing liquid is generally passed through this type of scrubber in a direction crosscurrent or countercurrent to the gas flow.

The fixed bed scrubber is not often used strictly for particulate pollutant collection. Operating problems have been encountered when this type of collector is utilized to clean a gas stream containing an excessively high concentration of particulate material. Therefore, in conjunction with this type of equipment, some form of dry collection equipment is used that eliminates much of the particulate load on the wet scrubber and helps prevent clogging.

The floating bed units, in which the packing is supported by the upward motion of the exhaust gas stream, are reported to be more resistant to clogging caused by particulate collection than the fixed packed bed units.[2186,0304] This reported increased ability to handle particulate contaminant is attributed to the relative motion between the packing materials which produces a self-cleaning action and allows the collected particulate material to be removed by the liquid flow. High particulate removal efficiencies (95 to 98 percent) have been reported for floating bed scrubbing units.

A condition known as flooding occurs when the upward gas velocity in the packed tower reaches a point at which there is a hold-up of liquid phase on the packing. In this condition, the liquid held in the packing builds up and eventually increases the pressure drop across the packed tower unit to the point where liquid will be entrained and carried out with the exhaust stream. Care must be taken in the design and operation of tower equipment to ensure that this flooding condition is avoided and a reasonable pressure drop is maintained. Properly designed packing materials allow a high liquid surface area to be maintained within the scrubber. Operation at proper liquid-to-gas flow ratios can achieve high gaseous pollutant removal at relatively low gas flow resistances. Packing materials commonly used are plastic materials of various shapes, including rings, spiral rings, berl saddles, and other shapes which allow a high ratio of surface area to volume.

Utility consumption for the packed bed scrubber depends on the design of the bed, the packing material used and the collection efficiency desired. Typical water consumption for the packed bed scrubber ranges from

5 to 10 gpm per 1,000 CFM. Normal packed scrubber design dictates a pressure drop of from 1 to 10 in. of water with a total horsepower requirement of 0.3 to 2.8 for fan and pumping costs. Efficiencies of 95 to 98 percent have been realized for both particulate and gaseous control, although not necessarily concurrently.

The choice between crossflow and countercurrent scrubber design is dependent on the particular application. However, generally the crossflow scrubber is applied to situations where the bed depth is less than 6 ft and countercurrent design is applied at bed depths of 6 ft or more. These applications are based on the lowest combination of installed capital cost and operating cost.

Wet Cyclone Scrubbers

Wet cyclones are characterized by tangential entry of the air stream to be cleaned. The air stream passes through the collector in a spiral path. The liquid stream is directed outward from the center of the circular collection chamber. The cyclonic scrubber thus possesses some of the characteristics of both the simple dry cyclone collector and the spray chamber.

Particulate collection is accomplished by combining centrifugal acceleration of the particles toward the chamber wall with the action of the spray droplets in contacting and removing the particle. Particulate collection efficiences are generally in excess of 90 percent for particles 5 microns or larger. Gaseous pollutant capture is produced by the intimate turbulent contact between the exhaust gas stream and the liquid particles generated by spray nozzles and air stream shear forces within the scrubbing unit. Liquid requirements are generally on the order of 2 to 10 gal. of water per 1,000 cubic feet of gas treated. Gaseous collection efficiencies range up to 99 percent with pressure drops of 1 to 8 in. of water. Total fan and pump horsepower vary from 1 to 2 per 1,000 CFM. Wet cyclones have been designed to treat up to 100,000 CFM.

In summary, the wet cyclone has desirable characteristics when the gas stream to be cleaned contains both particulate and gaseous materials. The wet cyclone has an adequate capacity for handling high input dust loadings and produces acceptable collection efficiencies for both medium sized (>5 microns) particulate and gaseous pollutants. Where extremely high particulate collection efficiencies are required, however, the wet cyclone is used in conjunction with higher efficiency collection units. The purchase, installation and operating costs associated with cyclonic scrubbers are comparable with those of packed bed units for situations where the exhaust gas stream to be cleaned represents a high gas flow rate; however, the cyclonic scrubber requires less maintenance.

Self-Induced Spray Scrubbers

In this type of scrubber, the gas liquid contact is created as a result of impingement of the carrier gas upon a liquid. The performance characterisitics are thus dependent upon the gas flow rate through the collector. The effluent gas stream to be cleaned is impinged upon the surface of the scrubbing liquid; the scrubbing liquid is fragmented and broken into droplet-sized particles by the kinetic energy in the gas stream. The liquid droplets formed are entrained, and the effluent gas stream is passed through further sections in which turbulent contact between the liquid and gas phases occur.

Particulate collection efficiency approaches 90 percent for particles 2 microns and larger. For medium efficiency collection units of this type, pressure drops range between 3 and 6 in. of water. The entrained water droplets and the collected particulate material are removed in the final demisting stage of the induced spray scrubber.[2187] This type of equipment is particularly applicable to gas streams with high dust loadings since continuous removal of sludge can be accomplished with the installation of a screw convenyor. No pumping horsepower is required since the water remains at essentially atmospheric pressure and is atomized by the gas stream.

Another advantage of the induced spray collector lies in the fact that construction does not involve close clearances or small orifices. Clogging, which often represents the bulk of the maintenance problems in wet collectors, would not be expected under normal operating conditions.

Gaseous collection efficiency in the self-induced spray scrubber has been reported to be greater than 99 percent removal. The control system reported in these observations was a two-stage scrubbing operation with sequential induced spray collectors. Liquid-to-gas requirements are generally lower for this type unit than for most other wet collectors. Liquid requirements range between 1/4 to 3 gal of liquid per 1,000 cubic feet of gas. Fan horsepower for head recovery is from 0.7 to 1.4 per 1,000 CFM of treated gas.

Orifice Plate Bubblers

The orifice plate bubbler is a class of wet impingement scrubber. The gas stream to be cleaned is passed through a perforated plate and impinged on baffles where the gas jets attain maximum velocity. The impingement baffles are covered by a layer of scrubbing liquid during operation. The gas stream passing through the baffle plate prevents the flow of liquid through the perforated plate. Intimate mixing of the gas streams and the liquid occurs facilitating both gas transfer to the liquid phase and particulate collection by the scrubbing liquid.

Particulate collection efficiencies from 90 to 95 percent have been reported for 2-micron diameter dust particles. Several stages of perforated plate and impingement baffle may be assembled into a single collector unit. The particulate removal efficiency is directly related to the number of plates used in the scrubber. As is usual in the design of wet collectors, a mist eliminator is used following the last baffle plate section. Pressure drop through the impingement baffle system has been reported between 1 to 10 in. of water depending upon the size and number of perforations used, and the number of impingement plates in the collector.[2188]

Gaseous pollutant removal efficiencies between 99 and 99.5 percent have been reported for orifice plate bubblers. High collection efficiencies for both particulate and gaseous pollutants make this unit applicable in a wide range of control situations. Water usage runs from 1 to 5 gpm per 1,000 CFM and the total (fan and pump) horsepower requirements range from 0.5 to 3 per 1,000 CFM.

Clogging has not proved to be a problem in this equipment even though the perforations in the plate are typically only 1/4 in. or less in diameter. Clogging is prevented by high (75 ft/sec or more) gas velocities through these orifices which agitate the liquid on the surface of the plate and keep the dust particles in suspension.

Venturi Scrubbers

The basic distinguishing design feature of the venturi scrubber is the passage of the exhaust gas stream through a venturi-type constriction. In this constriction, high linear gas velocities on the order of 12,000 to 42,000 ft per minute are attained. The scrubbing liquid is usually introduced normal to the gas flow at or near the minimum flow area of the venturi. The high gas velocity at this point atomizes the scrubbing liquid into fine droplets that are maintained in turbulent contact with the gas stream.

Particulate collection efficiencies in the venturi scrubber are directly related to the gas phase energy input. Gas pressure drops of 10 to 100 in. of water are common in this type unit with particulate collection efficiency for submicron particles approaching 99 percent at the higher pressure drops. The freedom from clogging afforded by the relatively simple liquid distribution system of this type unit makes possible the treatment of exhaust streams containing high dust loads. The high particulate removal efficiency further makes the venturi scrubber most applicable when particulate removal is of primary importance.

The intimate gas-liquid contact obtained in this type unit allows the efficient removal of gaseous as well as particulate pollutants. Gaseous pollutant removal efficiencies from 80 to 99 percent have been reported. The venturi pressure drops associated with these reported efficiencies ranged from 15 to 50 in. of water.[2188] Scrubber liquid requirements for this type of control equipment range from 3 to over 8 gal per 1,000 cubic feet of gas.

Jet Scrubber

Another type of scrubber operated on the venturi principle is the jet scrubber or ejector venturi design. As in the case of the standard venturi scrubber, the basic operating principle consists of passage of the exhaust gas flow through a restrictive orifice. In the ejector venturi design, the energy impelling the gas stream through the orifice comes from a high pressure liquid spray rather than from the gas phase pressure drop across the collecting unit i.e., water is used to aspirate the dust-laden gas through the ejector. The ejector provides the head for the gas, although large induced drafts (above several inches of water) are usually avoided to maintain a high entrainment ratio since larger entrainment ratios require less water for a given gas flow rate. Typical water usage ranges from 50 to 100 gpm per 1,000 CFM with a pressure drop of 50 to 100 psi for the water across the ejector. This amounts to 1 to 5 pump hp per 1,000 CFM. Particulate and gaseous collection efficiencies experienced with the ejector venturi design are comparable with those attained in conventional venturi scrubbing. In both devices, the air stream is brought into intimate and turbulent contact with a fine droplet spray.

The jet scrubber is usually followed by a baffled or settling chamber to capture the water treated particulate matter and water droplets. The main use for this type of equipment is in situations where it is not economical to add a fan to the system. A wide range of sizes is available in this type of collection unit and multiple banks of ejector venturis have been used to control large process emission sources.

Dynamic Wet Scrubbers

In the dynamic wet scrubber, liquid is mechanically sheared into fine droplets and then contacted with the dust laden gas stream. The shearing usually is accomplished by injecting the water into fan blades which simultaneously mix the water and dust streams and recover the lost pressure head of the effluent stream. The wetted impeller and a housing hold the collected dust particles and prevent re-entrainment. The dust collection efficiency is approximately 95 percent for 1 micron particles. Although no pressure drop is incurred by the process stream, there is a 3 to 20 hp/1,000 CFM requirement for the fan to disperse the water and recover the head. Many of the higher horsepower dynamic units are being displaced with venturi scrubbers. Typical water consumption varies from 3 to 5 gpm per 1,000 CFM. Good gaseous collection efficiencies can be expected from the dynamic wet scrubber because of an intimate mixing of the water and the process stream.

3. DRY REMOVAL SYSTEMS[2188,1673,218]

Dry removal systems are generally used as primary treatment systems and have little effect on gaseous pollutants. Under certain conditions, dry collection systems have been applied to effluent streams either to decrease the particulate load on subsequent control equipment or to collect a solid adsorbant that has been used to reduce the stream's gaseous pollutant content. In either case, the dry collection equipment is usually followed by secondary or even tertiary treatment. Three main classes of dry collection equipment are available: mechanical collection equipment, electrostatic precipitation, and fabric filtration.

Mechanical Collectors

Mechanical collectors (inertial separators) have proven to be reliable collectors of dry particulate material in a number of air pollution control applications. These devices collect particulate material by the use of centrifugal force, gravitational force, or by rapid changes in the direction of the dust laden stream. Mechanical devices are simple to construct, relatively inexpensive, and operate at moderate pressure drops. Generally, the efficiency of the mechanical collector will increase markedly with increased dust loadings, thus, it is often used as a precollector for more efficient control equipment which is susceptible to overload. Common types of dry mechanical collectors employed in industry include the settling chamber, the louver type collector, the cyclone, the impingement collector, and the dynamic collector.

Settling Chamber. The settling chamber directs the dust laden gas into an oversized duct where the gas velocity drops to a point where the entrained particles drop out because of the force of gravity. This type of equipment is used in relatively high particulate concentrations (above 5 grains/ft^3) with particles sizes of 50 microns or larger. Dust collection efficiencies range from 50 to 90 percent depending on dust particle size distribution. The pressure drop through the settling chamber ranges from 0.2 to 0.5 in. water gage (wg) resulting in a low fan horsepower requirement of 0.04 to 0.12 per 1,000 CFM of treated gas. Since the efficiency of the settling chamber is relatively low for dispersoid particulates and has no effect on gaseous pollutants, this type of equipment is generally used for pretreatment of a gaseous stream that is to be fed to some more efficient type of collection device. The volume of gas that is treated by this type of equipment is limited only by the space available for the unit designed to treat that volume. The typical gas velocity through the chamber ranges from 5 to 10 ft per second.

Baffle Chamber.[2189] In the baffle chamber, settling is aided by using the momentum of the heavy particulate matter to separate it from the carrier gas. The dust laden gas enters the baffle chamber and is directed downward around a baffle and out the top of the chamber. The heavy dust particles tend to continue moving downward and are separated from the gas stream. They drop out a small opening in the bottom of the chamber and are collected. The baffle chamber is used for the same type of conditions as is the settling chamber with the advantage of a smaller space requirement. Gas velocities of 20 to 40 ft per second are typical in the baffle chamber with a pressure drop of 0.1 to 0.5 in. of water. The fan horsepower requirement needed to compensate for this pressure drop is 0.02 to 0.12 per 1,000 CFM of treated gas. The baffle chamber has a collection efficiency of from 50 to

90 percent depending on the dust particles to be removed (usually above 50-micron diameter).

Skimming Chamber.[2189] The skimming chamber is similar to the baffle chamber in that it uses the greater momentum of the dust particles to separate them from the gas stream. The dirty gas stream enters an enclosed metal scroll tangentially and the dust is carried to the edge by inertia. A concentrated dust stream is skimmed from the edge of the scroll and sent to a secondary chamber. Gas velocities of 35 to 70 ft per second are typical for this type of equipment. Efficiencies of 70 percent are obtainable with particles 20 microns in diameter. Pressure drops of up to 1 in. of water can be expected with a resulting horsepower requirement of from 0.02 to 0.24 per 1,000 CFM. The limiting size for this type of equipment is 50,000 CFM.

Louver Type Collectors[2189] This type of equipment also employs the difference in momentum between the dust particles and the carrier gas to separate out the dust. The incoming gas must make a sharp bend in order to escape through the louver (slots) in the wall. The heavier dust particles are carried to the end of the apparatus where they are carried out by a small portion of the original gas stream in a concentrated stream. Efficiency of 80 percent can be obtained on 20-micron particles at gas velocities of 35 to 70 ft per second. Flow rates are limited to 30,000 CFM for this type of equipment. A pressure drop of 0.5 to 2 in. of water can be expected through this type of equipment requiring from 0.12 to 0.48 fan hp per 1,000 CFM to return the gas stream to pretreatment pressure conditions.

Dry Cyclones.[2189] In a cyclone, the dust laden gas enters the top of the apparatus tangentially, forming a vortex that extends downward toward the bottom of the cone-shaped base. At this point the gas then reverses its direction and moves up the center of the outer vortex in a vortex core. The separation of the dust occurs during the downward flow of gas when the inertia of the particles forces them out of the gas stream toward the wall of the cyclone. At the bottom of the cone, the particles continue to move downwards because of their momentum in that direction and are collected through a hole at the base of the cone.

The simple cyclone is typically applied to streams up to 50,000 CFM and can obtain 50 percent efficiency on 20-micron particles. Pressure drops of 0.5 to 3 in. of water are typical with gas velocities of 35 to 70 ft per second. Fan horsepower requirements are from 0.12 to 0.74 per 1,000 CFM to recover the lost pressure head.

There are several modifications of the simple cyclone also employed as dust collection equipment. The high efficiency cyclone employs a relatively small diameter and higher gas velocities in order to obtain a greater efficiency. Efficiencies of 80 percent have been obtained on 10-micron particles. Flow rates in this type of cyclone are limited to 12,000 CFM with an increased pressure drop of 3 to 5 in. of water because of the increased gas velocities. The larger pressure drop dictated by this equipment requires a proportionally larger fan horsepower requirement in order to recover the lost pressure head. Another common variation on the simple cyclone is the multiple cyclone in which many small diameter cyclones are employed to treat the same amount of gas as a conventional cyclone. The effect of this approach is to decrease the effective diameter and increase the efficiency. An efficiency of 90 percent is nominal for 7.5-micron particles. The pressure drop and fan horsepower for the multiple cyclone is similar to the high efficiency cyclone.

Impingement Collector.[2189] The impingement collector also uses the higher momentum of the dust particles to separate them from the carrier gas. The dirty gas is accelerated by a venturi and the particle momentum carries the dust particles through a slot in a facing metal plate where they impinge on another plate and are collected. The carrier gas tends to diffuse away from the path of the dust particles. It strikes the first metal plate and is carried away rather than going through the slot. This type of equipment can produce 90 percent efficiency on 10-micron particles with a pressure drop of from 1 to 2 in. of water. Almost unlimited flow rates are handled by impingement equipment with gas velocities of from 50 to 100 ft per second. Fan horsepower requirements for head recovery are from 0.24 to 0.48 per 1,000 CFM.

Dry Dynamic Collector.[2189] The dry dynamic collector is unique in that it uses a specially designed fan to separate the dust particles from the carrier gas and thus has no effective pressure drop. The gas stream is drawn into the collector and accelerated by the impellers of the fan causing the heavy dust particles to be thrown to the outside of the fan chamber. Here they are collected as a concentrated stream and sent to a hopper where they settle out. Since the dynamic collector employs a fan, there is no pressure drop through the equipment and the only utility required for this equipment is the horsepower for the collector itself. The horsepower required for a dynamic collector is slightly greater than that for a fan utilized for the same duty, since the mechanical efficiency is somewhat smaller for the collector. Normally the dynamic collector can handle up to 17,000 CFM of dirty gas with efficiencies of 80 percent on 15-micron particles.

Electrostatic Precipitation[2188]

Electrostatic precipitators use an electrical field for charging the particles in the incoming, pollutant-laden gas causing the charged particles to migrate to a collecting electrode because of the electrical field. Particles are collected on the opposite-polarity electrode and transferred to storage for disposal. Control equipment of this type has had extensive application in many fields of pollution control. A primary advantage of electrostatic precipitators is the relatively low operating costs of these units. Power requirements are low with the gas pressure drop rarely exceeding 1/2 to 1 in. of water. Additional power must, of course, be supplied in the form of electric energy required to ionize and collect the particulate material. The total power requirements for electrostatic precipitator units, however, are low compared with power requirements to attain equivalent efficiencies with other collecting mechanisms; they range between 0.1 and 0.6 kw per 1000 CFM. Electrostatic precipitation units are commonly designed to operate at greater than 90 percent particulate removal efficiencies on particles of 2 microns or less with gas flow rates from 10,000 to 2,000,000 CFM. The initial cost (purchase and installation) of electrostatic precipitation equipment is high relative to initial costs for mechanical collectors or wet scrubbing systems.

Fabric Filtration[2188]

The third class of dry collection equipment which must be considered is fabric filters. In this type of unit, the exhaust gas stream to be treated is passed through a fabric filter bag which collects the particulate material in the exhaust gases while allowing the gases to pass through to the stack for emission. Very large areas of fabric are used to filter gas streams. The pressure drop or resistance to air flow in fabric filter units increases as the dust loading builds up on the fabric. In general, the pressure drop for this type of unit is between 5 and 10 in. of water. Various cleaning mechanisms are used periodically to remove collected particulate material from the fabric filters.

Particulate collection efficiency for this type of unit often exceeds 99.5 percent. Fabric filter units are relatively unaffected by dust loading or gas throughput up to their design capacity. For this reason they represent one of the most positive and efficient particulate control devices available. When used in conjunction with a solid adsorbent substance, fabric filtration can achieve a high degree of gaseous pollutant removal.

Fabric filtration suffers from two major limitations. Humid gas streams cause problems because of caking and binding of the collected particulate material on the fabric surface. This causes greatly increased pressure drop and, in some cases, prevents air flow through the filter installation. The second major limitation is in the cleaning of high temperature exhaust gases. Certain fabric filter materials, such as glass fibers and aromatic polyimide fabrics, have the ability to withstand exhaust gas streams up to 550 F. For gas temperatures above this level, or when it is desirable to use less expensive filtering materials such as nylon, cotton or wool, the gas stream must be cooled prior to entry into the fabric filter unit.

REFERENCES

0053. DeMarco, J., D. J. Keller, J. Leckman, and J. L. Newton. Incinerator guidelines 1969. Public Health Service Publication No. 2012. Rockville, Maryland, Bureau of Solid Waste Management, 1969. 105 p.

0167. IIT Research Institute. Utilization of red-mud wastes for lightweight structural building-products. Final report prepared for the U. S. Department of the Interior, Bureau of Mines under Contract No. 14-09-0070-382, May 1968. 41 p.

0285. Lund, H. F. Industrial pollution control handbook. 1 v. New York, McGraw-Hill Book Company, 1971.

0304. Ross, R. D. Industrial waste disposal. New York, Van Nostrand Reinhold Book Corporation, 1968. 340 p.

0534. Jones. H. R. Environmental control in the organic and petrochemical industries. Park Ridge, New Jersey, Noyes Data Corporation, 1971. 264 p.

0582. Witt, Jr., P. A. Disposal of solid wastes. Chemical Engineering, 78(22):62-78, Oct. 4, 1971.

0862. Danielson, J. A., comp. Air pollution engineering manual. Report prepared for the U. S. Department of Health, Education and Welfare by Air Pollution Control District, County of Los Angeles. Washington, U. S. Government Printing Office, 1967. 892 p.

0958. Department of the Army, Edgewood Arsenal. Transportable disposal systems, environmental statement. Special publication, EASP 200-11, July 1971. 297 p.

0976. Prenco. Prenco brochure; the modern approach to liquid pollution control. Detroit, Michigan, Pickands Mather and Company. 7 p.

1002. Novak, R. G. Eliminating or disposing of industrial solid wastes. Chemical Engineering, 77(21):79-82, Oct. 5, 1970.

1435. John Zink Company. NO_x destructor. Tulsa, Oklahoma.

1456. Personal communication. J. Feldstine, Hirt Combustion Engineers, to M. Santy, TRW Systems, Mar. 21, 1972.

1459. Personal communication. R. Stattenbenz, Air Preheater, to M. Santy, TRW Systems, Mar. 21, 1972.

1460. Personal communication. C. Cantrel, John Zink Company, to M. Santy, TRW Systems, Mar. 21, 1972.

1461. Personal communication. J. Brewer, UOP, Air Correction Division, to M. Santy, TRW Systems, Mar. 21, 1972.

REFERENCES (CONTINUED)

1465. Dorr-Oliver. The Dorr-Oliver FS disposal system. Bulletin No. 6051.

1466. Alford, J. M. Sludge disposal experiences at North Little Rock, Arkansas. *Journal of the Water Pollution Control Federation,* 41(2):175-183, Feb. 1969.

1533. Brewer, G. L. Fume incineration. *Chemical Engineering,* Oct. 14, 1968.

1534. Pauletta, C. Incineration. *In* Pollution Engineering, Mar./Apr. 1970. p. 1.

1574. Lewis, F. M. Discussions of papers presented at the 1968 National Incinerator Conference, New York, May 5-8, 1968. American Society of Mechanical Engineers. p. 1.

1575. Bertrand, R. R., J. T. Sears, and A. Skopp. Fluid bed studies of the limestone based flue gas desulfurization process. Interim Report Oct. 15, 1967-Feb. 15, 1969 prepared for National Air Pollution Control Administration by Esso Research and Engineering Company, Linden, New Jersey under Contract No. PH 86-67-130. Washington, U. S. Government Printing Office, 1969.

1576. Bertrand, R. R., A. C. Frost, and A. Skopp. Fluid bed studies of the limestone based flue gas desulfurization process. Interim Report Oct. 31, 1968 prepared for National Air Pollution Control Administration by Esso Research and Engineering Company, Linden New Jersey under Contract No. PH 86-67-130. Washington, U. S. Government Printing Office, 1969.

1580. Airpollutionomics UOP catalytic incineration systems. Bulletin No. 602. Darien, Connecticut, May 1971. 12 p.

1661. PCB retreats again. *Chemical Week,* 110(5):14-15, Feb. 2, 1972.

1672. Bartlett-Snow Company. Tumble-burner, advertising brochure. Bulletin 205B. Cleveland, Ohio, 1970. 6 p.

1673. Perry, R. H. Chemical engineers handbook. 3d ed. New York, McGraw-Hill Book Company, 1969.

1688. Honea, F. I., J. Wichmann, and W. A. Bullerdick. Disposal of waste or excess high explosives. Progress Report, Jan.-Mar. 1972, prepared for U. S. Atomic Energy Commission, Albuquerque Operations Office by Mason & Hanger - Silas Mason Company, Inc.

1689. TRW internal correspondence. G. I. Gruber to R. S. Ottinger, Apr. 7, 1972. Trip report Mar. 22-24, 1972 (Mason and Hanger; Olin Company: Army Materiel Command)--Hazardous Waste Disposal.

REFERENCES (CONTINUED)

1701. Personal communication. E. Dolsak, Bartlett-Snow Company, to M. Santy, TRW Systems, May 11, 1972.

1702. John Zink Company. Waste liquid burner. Tulsa, Oklahoma. Bulletin DB 0267.

1703. John Zink Company. Information on pollution control. In Chemical Processing. Jan. 1972.

1761. Sebastian, F. P., and P. J. Cardinal. Solid waste disposal. Chemical Engineering, Oct. 14, 1968. p. 112-117.

1792. Airpollutionomics UPO thermal incineration systems. Bulletin No. 607. Darien, Connecticut. 8 p.

2186. Kiflback. A. W. The development of floating bed scrubbers. Chemical Engineering Progress, 57(35):51-54, 1961.

2187. Doyle, H. The Doyle scrubber. Industrial and Engineering Chemistry, 49(12):57-62, Dec. 1957.

2188. Caplaa, K. J. Wet collectors and adsorption of gases. Air Pollution Manual, Part 2-Control Equipment. Detroit, Michigan, American Industrial Hygiene Association, 1968. p. 1-110.

2189. Sargent, G. D. Dust collection equipment. Chemical Engineering, 72(2):130-150, Jan. 27, 1969.

PYROLYSIS

1. INTRODUCTION

Pyrolysis is generally defined as the thermal decomposition of a compound. With respect to waste carbonaceous materials, pyrolysis represents a means of converting the unwanted waste into a usable commodity with economic value. That is, most municipal and industrial wastes which are basically organic in nature can be converted to coke or activated charcoal and gaseous mixtures which may approach natural gas in heating values through the utilization of pyrolysis.[1011, 1433]

Pyrolysis has only recently (1968) been applied to the conversion of organic wastes. The process has traditionally been used to convert low economic value homogeneous materials, such as wood chips and heavy hydrocarbon still bottoms, to compounds with higher overall economic value, such as fuel gas, pitch, creosote, acetic acid, crude methanol and charcoal (as in the case with wood chips), and coke, fuel gas and gas oil (as in the case with still bottoms).[1433,1662] For purposes of this report, only the methods associated with waste conversion will be discussed.

2. OPERATION PRINCIPLE[0145,1009]

The heart of the pyrolytic waste conversion process is the pyrolytic converter (Figure 1). The unit consists of a sealed, airtight retort cylinder inside a heavy insulating jacket. The gas-fired retort revolves slowly on a slight decline from infeed to outfeed. Wastes are injected through a seal area that intermittently opens (the flapper valve seal is designed to minimize entry of oxygen).

Inside the retort, ground-up wastes are subjected to temperatures of about 1,200 F - plus or minus 300 F, depending upon the nature of the wastes, in an essentially oxygen-free atmosphere. Without oxygen, the wastes cannot burn and are broken down (pyrolyzed) into steam, carbon oxides, volatile vapors and charcoal.

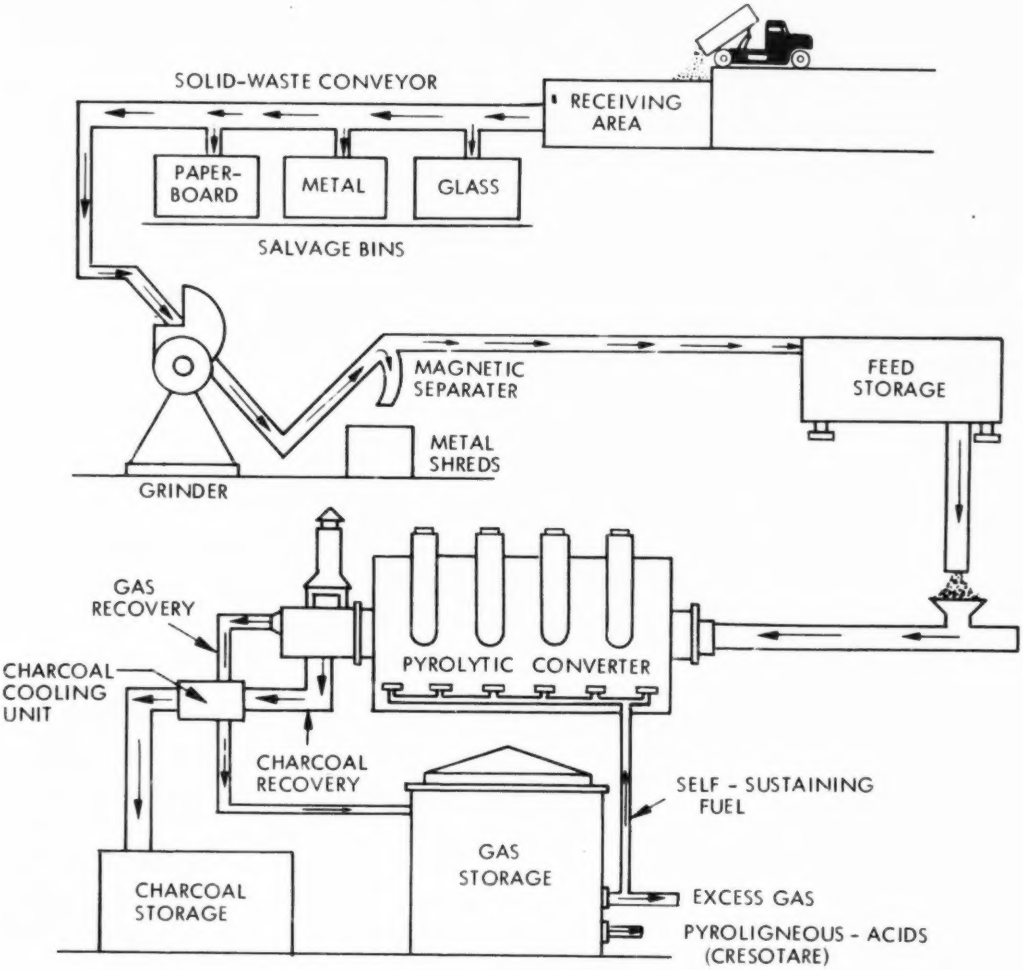

SOLID-WASTE CONVEYOR
RECEIVING AREA
PAPER-BOARD
METAL
GLASS
SALVAGE BINS
MAGNETIC SEPARATER
FEED STORAGE
METAL SHREDS
GRINDER
GAS RECOVERY
CHARCOAL COOLING UNIT
PYROLYTIC CONVERTER
CHARCOAL RECOVERY
SELF - SUSTAINING FUEL
GAS STORAGE
EXCESS GAS
CHARCOAL STORAGE
PYROLIGNEOUS - ACIDS (CRESOTARE)

Figure 1. Pyrolytic waste conversion[1009]

Steam, carbon dioxide and carbon monoxide are the first gases to emerge. They are trapped and then: (1) vented after flaring; (2) used to dry incoming feed; or (3) the steam can be condensed and the effluent gas burned for fuel value.

As the wastes are heated further, volatile gases are distilled. Typically, these gases will include hydrogen, methane, ethylene and ethane. About 25 cubic ft of combustible gases are recovered from m every pound of industrial and municipal refuse. Energy value per cubic foot is usually between 400 and 500 Btu.

The crude, combustible gas is drawn off and used in part (30 to 40 percent) to fuel the converter while the remainder may be utilized to fuel other equipment or to make steam for such uses as heating and power generation.

In fact, a 100-ton per day municipal waste conversion facility will produce enough excess gas to create 400,000 kilowatts of electricity per day. At a quarter-cent per KW, that amounts to $1,000 of electrical energy per day. Thus, recovery of combustible gas usually offsets the total operating costs of a waste-conversion facility.

The surplus gas cannot be piped over any great distance and retain its original heat value. Nor can it be stored. For, allowed to cool, pyroligneous acids begin to condense, reducing heat value per cubic foot to around 350 Btu and reducing volume by as much as 80 percent.

However, the liquid condensate is of economic value. It constitutes a form of cresotar which is used for, among other things, dust control on unpaved roads. Moreover, the liquid represents a potentially valuable source of organic compounds. Chemical analyses have identified such constituents as methanol, ethanol, isobutanol, n-pentanol, tert. pentanol, 1,3-propanedial, 1-hexanol, acetic acid and various other alcohols, ketones and tars.

The last by-product is charcoal. Generally 30 to 35 percent of input by weight is recovered in this form, and each pound of charcoal has an approximate heat value of 12,000 Btu. Used as fuel, it can create about half the electricity expected from the recovered gas.

Other major pieces of equipment required for a municipal or industrial waste-conversion facility are a hogger/grinder, a magnetic separator, conveyors, and storage facilities. A hogger/grinder is necessary because converters generally operate best when solid waste materials are reduced to no more than a few inches in size. Since pyrolysis units do not usually vent any products to the atmosphere, they do not require any air pollution control equipment.

3. PROCESS DESIGN[0145, 1009]

Pyrolytic conversion processes are generally custom-engineered according to input volumes and types of waste being treated. For this reason, there is not a great deal of specific design information available. Converters have been made with capacities ranging from 1/4 ton to 12 tons per hour. Units can be installed in batteries to handle more than 12 tons per hour. For instance, one municipal pyrolytic process utilizes four 4-ton per hour converters.

Intake-to-discharge cycles vary with heat intensity, the converters length, and its rotational speed. The average for industrial and municipal refuse is 12 to 15 minutes. Such hard to pyrolyze materials as coal (which is converted into coke) and rubber may take as long as 30 minutes.

Operational temperatures will vary with waste type and desired products. Operating temperatures are usually in the 1,200 F ± 300 F range with the lower operating temperature generally resulting in greater residue (coke), tar and light oil yields and lower gas yields (Tables 1 and 2).

TABLE 1.

YIELDS OF PRODUCTS FROM PYROLYSIS OF MUNICIPAL AND INDUSTRIAL REFUSE 0145

Refuse	Pyrolysis temp, F	Yields, weight-percent of refuse							Yields per ton of refuse				
		Residue	Gas	Tar	Light oil in gas	Free ammonia	Liquor	Total	Gas, cubic feet	Tar, gallons	Light oil in gas, gallons	Liquor, gallons	Ammonium sulfate, pounds
Raw municipal	930-1650	9.3	26.7	2.2	0.5	0.05	55.8	94.6	11,509	4.8	1.5	133.4	17.9
	1380	11.5	23.7	1.2	.9	.03	55.0	92.3	9,628	2.6	2.5	131.6	23.7
	1650	7.7	39.5	.2	-	.03	47.8	95.2	17,741	.5	-	113.9	25.1
Processed municipal containing plastic film	930-1650	21.2	27.7	2.3	1.3	.05	40.6	93.2	11,545	5.6	3.7	96.7	16.2
	1380	19.5	18.3	1.0	.9	.02	51.5	91.2	7,380	2.2	2.6	122.6	28.4
	1650	19.1	40.1	.6	.2	.04	35.3	95.3	18,058	1.4	.6	97.4	31.5
Industrial-Sample A	930-1650	36.1	23.7	1.9	.5	.05	31.6	93.9	9,563	4.1	1.4	75.2	12.5
	1380	37.5	22.8	.7	.9	.03	30.6	92.5	9,760	1.5	2.6	73.0	19.5
	1650	38.8	29.4	.2	.6	.04	21.8	90.8	12,318	.5	1.6	51.1	21.7
Industrial-Sample B	930-1650	41.9	21.8	.8	.6	.03	29.5	94.6	9,270	1.7	1.6	70.2	20.4
	1380	31.4	25.5	.8	.8	.03	31.5	90.0	10,952	1.8	2.2	74.9	21.2
	1650	30.9	31.5	.1	.5	.03	29.0	92.0	14,065	.02	1.4	68.5	22.9

TABLE 2.

TABLE 2. CHEMICAL ANALYSES* OF SOLID RESIDUES FROM PYROLYSIS OF MUNICIPAL AND INDUSTRIAL REFUSE 0145

Refuse	Pyrolysis temp, F	Proximate, percent				Ultimate, percent					Heating value, Btu/lb	Heating value, million Btu/ton
		Moisture	Volatile matter	Fixed carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulfur		
Raw municipal	930-1650	2.6	4.4	29.6	66.0	0.4	32.4	0.5	0.5	0.2	5,020	10.040
	1380	2.2	7.4	51.4	41.2	.8	54.9	1.1	1.8	.2	8,020	16.040
	1650	1.0	4.7	31.7	63.6	.3	36.1	.5	.0	.2	5,260	10.520
Processed municipal containing plastic film	930-1650	1.7	4.8	56.7	38.5	.6	57.7	.8	2.1	.3	8,800	17.700
	1380	1.3	13.4	34.6	52.0	.8	41.9	.8	4.4	.1	6,080	12.160
	1650	1.2	3.3	53.5	43.2	.5	53.4	.7	1.8	.4	8,090	16.180
Industrial - Sample A	930-1650	.9	2.6	15.2	82.2	.3	17.0	.1	.2	.2	2,520	5.040
	1380	1.2	5.1	17.0	77.9	.5	19.4	.2	1.8	.2	2,900	5.800
	1650	.1	2.5	12.9	84.6	.3	14.8	.2	.0	.2	2,180	4.360
Industrial - Sample B	930-1650	.3	3.0	9.7	87.3	.2	11.8	.1	.4	.2	1,660	3.320
	1380	1.0	3.6	16.6	79.8	.3	19.5	.2	.0	.2	2,680	5.360
	1650	.2	6.4	16.2	77.4	.4	19.3	.3	2.4	.2	2,810	5.620

* Moisture on as-received basis; all other data on dry basis.

4. PROCESS ECONOMICS[0582, 1010]

The primary factors determining the capital cost of pyrolysis systems include waste flow rate, waste composition, secondary effluent treatment for product recovery, and materials of construction. Operating costs are determined by labor rates, maintenance requirements, and conversion product values.

An exhaustive economic analysis of a commercial size (5,000 tons/day) municipal refuse pyrolysis plant was made in 1970 by Cities Service Oil Company.[1010] The study indicated that a total investment including working capital) of 32.6 million dollars was required and that the associated operating cost would be $2.14 per ton of refuse pyrolyzed (Table 3). There is no economic data available with respect to industrial waste pyrolysis processes.

5. PROCESS MODIFICATIONS[0582,1010]

Modifications to the pyrolysis process generally involve treatment of converter effluents (Figure 2). The pyrolysis oils may be sent through a hydrotreating unit and converted to industrial fuel oil. The pyrolysis effluent gas may be cooled and the resultant condensate separated into its components, namely acetic acid, methanol, furfural, acetone, butyric acid, propionic acid, methyl ethyl ketone, light fuel oil, and other water soluble volatile organics, through the use of conventional separation techniques. The cooled wet gas may be dried and utilized as fuel gas. The char-like pyrolysis residue can be further treated and converted into activated carbon.

6. PROCESS APPLICABILITY

The utilization of pyrolytic processes to convert waste into useful materials is a relatively new concept. For this reason, there are few processes in operation today. Those processes which are in operation

TABLE 3

INVESTMENT AND OPERATING COSTS FOR A 1010 5000 TON/DAY MUNICIPAL PYROLYSIS PLANT

Capital Investment		
Investment	$ Million	
Inside battery limits	16.0	
Offsites	6.4	
Total	22.4	
Additional Costs		
Contingency (25%)	5.6	
Construction interest, first year (8% x 33%)	0.7	
Construction interest, second year (8% x 67%)	1.5	
Startup extraordinary (assumed 8% x 100%)	2.4	
Total additional costs	10.2	
Total investment (includes working capital)	32.6	
Operating Costs		
Fixed Costs	$ Million	(per year)
Labor	0.49	
Supervision	0.15	
Overhead	0.64	
Maintenance, onsite	1.00	
Maintenance, offsite	0.24	
Taxes and Insurance	0.49	
Total fixed costs	3.01	$1.65/ton
Variable Costs		
Water and power	0.20	
Fuel	0.70	
Total Variable Costs	0.90	$0.49/ton
Total Operating Costs	3.91	$2.14/ton

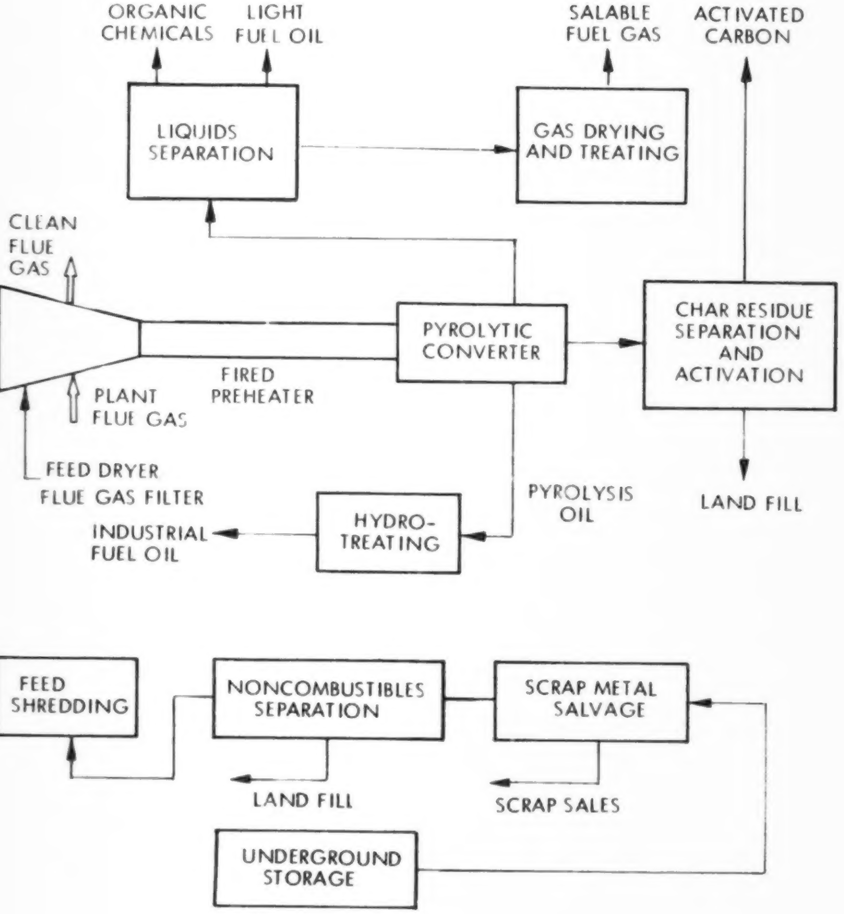

ORGANIC CHEMICALS
LIGHT FUEL OIL
SALABLE FUEL GAS
ACTIVATED CARBON
LIQUIDS SEPARATION
GAS DRYING AND TREATING
CLEAN FLUE GAS
PYROLYTIC CONVERTER
CHAR RESIDUE SEPARATION AND ACTIVATION
FIRED PREHEATER
PLANT FLUE GAS
FEED DRYER
FLUE GAS FILTER
PYROLYSIS OIL
LAND FILL
INDUSTRIAL FUEL OIL
HYDRO-TREATING
FEED SHREDDING
NONCOMBUSTIBLES SEPARATION
SCRAP METAL SALVAGE
LAND FILL
SCRAP SALES
UNDERGROUND STORAGE

Figure 2. Secondary Treatment Alternatives[0582]

convert municipal refuse, industrial refuse, paint sludges, tires, plastics and other organic polymers into materials with economic value.[1009,1011]

Although the pyrolytic converter is a versatile piece of equipment that can be operated under varying conditions with various feed materials, its auxiliary equipment tends to be specific for various feeds and desired end products. For that reason, the overall pyrolytic process tends to lack versatility.

At a National Disposal Site, a pyrolysis unit would probably find little direct application as a hazardous waste conversion unit. However, if sufficient refuse was generated at the site, a pyrolysis unit could be utilized to convert it into fuel gas for use in other operations (furnaces, incinerators, reboilers, boilers for steam production and possible subsequent conversion to electricity, etc.) and coke which could be utilized for its heat content or converted to activated carbon for use in water treatment facilities.

REFERENCES

0145. Sanner, W.S., C. Ortuglio, J. G. Walters, and D. E. Wolfson. Conversion of municipal and industrial refuse into useful materials by pyrolysis. U.S. Department of the Interior, Bureau of Mines, Report of Investigations 7428. Washington, U.S. Government Printing Office, Aug. 1970. 14p.

0582. Witt, P.A., Jr. Disposal of solid wastes. Chemical Engineering, 78(22):62-78, Oct. 4, 1971.

1009. Pyrolytic decomposition of solid wastes. Public Works, p.82,83 160, Aug. 1968.

1010. Rosen, B.H., R.G. Evans, P. Carabelli, and R.B. Zaborowski. Economic evaluation of a commercial size refuse pyrolysis plant. Cities Service Oil Company, Cranbury, New Jersey, Mar. 1970. 40 p.

1011. Chementator. Chemical Engineering, 75(26):53, Dec. 2, 1968.

1433. Kirk-Othmer encyclopedia of chemical technology. 2d ed. 22v. and suppl. New York, Interscience Publishers, 1963.

1662. Shreve, R.N. Wood chemicals. In Chemical process industries. 3rd ed. New York, McGraw-Hill Book Company, p.617-621, 1967.